DES ENVIRONNEMENTS PROFESSIONNELS ANALOGUES AU DÉFI SPATIAL :

Étude des réponses adaptatives au stress & contre-mesures de santé pour un maintien opérationnel sous contrainte

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Ecole Doctorale BioSE (Biologie-Santé-Environnement)

Thèse

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par **Barbara LE ROY**

Des environnements professionnels analogues au défi spatial :

Étude des réponses adaptatives au stress & contre-mesures de santé pour un maintien opérationnel sous contrainte

4 décembre 2023

Membres du jury :

Rapporteurs :

Madame Angélique VAN OMBERGEN, Professeure, Agence Spatiale Européenne, Noordwijk (Pays-Bas)

Monsieur Olivier GAPENNE, Professeur, Université de Technologie de Compiègne, Compiègne (France) président du jury

Examinateurs :

Monsieur Olivier MANEN, Professeur, Hôpital d'Instruction des Armées Percy, Clamart (France)

Madame Anne PAVY LE TRAON, Professeure, Institut de Médecine et Physiologie Spatiale, Toulouse (France)

Monsieur Charles MARTIN-KRUMM, Professeur, Institut Catholique de Paris, Paris (France) directeur de thèse

Madame Marion TROUSSELARD, Professeure, Institut de Recherche Biomédicale des Armées, Brétigny-sur-Orge (France) co-directeur de thèse

Membres invités :

Monsieur Henri MAROTTE, Professeur, Université Paris Cité, Paris (France)

Monsieur Sylvain LABORDE, Maître de Conférences, Université Allemande du Sport, Cologne (Allemagne)

UR 4360 Adaptation, mesure et évaluation en santé. Approches interdisciplinaires (APEMAC) Ile du Saulcy 57045 METZ

Per aspera ad astra

PRÉFACE

Note de l'auteur

Aujourd'hui s'achèvent trois années de doctorat. Nombreux sont ceux qui pourront mettre en évidence aussi bien les montagnes à gravir que les moments de joie qui les traversent. Depuis que mes yeux peuvent observer les étoiles, l'espace constitue un sujet d'émerveillement. J'ai eu cette opportunité de pouvoir explorer et étudier un sujet cher à mon âme. Je rêve de pouvoir un jour observer la courbure de notre Terre, que nous ayons suffisamment développé la technologie et la compréhension du fonctionnement humain pour visualiser l'Univers qui nous entoure. Les recherches dans ce domaine n'auront pas qu'une portée au-delà des frontières de la Terre mais serviront également à améliorer les conditions de vie des professionnels de l'extrême et des personnes faisant face à des situations de réelles vulnérabilités. Il n'est pas sans rappeler les mots de Nansen : *« Il est encore des gens pour croire qu'il ne sert à rien d'explorer les régions polaires inconnues. Cela prouve leur ignorance. Faut-il rappeler ici que leur exploration minutieuse a une immense portée scientifique ? L'histoire du genre humain est une lutte perpétuelle pour aller des Ténèbres à la Lumière. Disputer de l'utilité du savoir est donc sans objet. Quand l'homme cesse d'aspirer au savoir, il n'est plus homme* ».

Ce travail de recherche a également pour vocation de croiser plusieurs champs disciplinaires en passant des sciences cognitives, aux neurosciences, à la médecine, à la psychologie, à la physiologie, et pour finir aux nouvelles technologies et à l'intelligence artificielle. Ainsi, il reflète une réelle volonté d'apporter un regard nouveau, de créer des ponts entre les disciplines et une nouvelle perspective à un sujet qui, pris seul, n'aurait pas la même portée.

Cette Thèse est le travail d'une vie, et une passion de tous les instants. J'ai eu la chance et l'opportunité de vivre un rêve éveillé par l'ensemble des expériences menées. En passant du coin le plus reculé sur Terre en Tasmanie, aux tréfonds du désert de l'Utah, aux variations gravitaires en haute altitude avec l'astronaute français Thomas Pesquet, j'ai pu vivre des expériences peu communes qui m'ont nourries. Ce fut un voyage de pensée et de vie. Je n'oublierai jamais cet espace-temps au cours duquel j'ai vécu les moments les plus incroyables de mon existence. J'espère que la lecture de cette Thèse pourra vous transmettre toute l'émotion que j'ai pu ressentir et l'énergie que j'ai engagé au cours de ces trois années intenses.

Durant ces trois ans, j'ai développé des ailes. Je rêve de me fondre dans cette immensité noire et d'observer l'expansion de nos découvertes.

Mon rêve ultime reste de découvrir un jour de mes propres yeux celle que nous appelons notre maison : la Terre.

Atteindre les étoiles n'aura jamais été aussi proche qu'aujourd'hui. Décollons ensemble pour découvrir les sous-baissements de cette merveilleuse aventure.

Je vous souhaite une très belle lecture.

Barbara

Remerciements

Je tiens tout particulièrement à remercier mes directeurs de thèse, Marion Trousselard et Charles Martin-Krumm. Les mots ne peuvent exprimer l'affection et la gratitude que je leur porte. Ils ont su avoir confiance en moi lorsque je n'étais plus capable de voir la lumière du jour et me pousser au-delà de moi-même. Je me suis découverte grâce à eux et n'ai jamais autant grandi que sous leur supervision. Je leur serai éternellement reconnaissante de m'avoir apporté un chemin de vie. Ils ont su me transmettre cette passion pour la recherche et la science. Ils sont une véritable source d'inspiration au quotidien. Je n'aurais pu rêver mieux pour encadrer mes travaux de recherche. Au-delà de leur encadrement, j'ai trouvé une amitié sincère et profonde. Je fais le vœu que notre amitié reste éternelle au-delà de l'espace et du temps.

Aucune encre et aucun papier ne seraient assez importants pour exprimer mon affection à l'égard de Marion Trousselard. Depuis le début de notre relation en janvier 2019, tu as été une source aussi bien d'inspiration que de ressource. Tu es d'un soutien indéfectible et d'une grande admiration. Ta force et ton dévouement donnent envie d'accomplir de grandes choses. Je n'ai pas les mots pour écrire à quel point le dénouement de beaucoup de situations n'aurait pas été le même sans ta présence et tes conseils. Ta bienveillance, ta gentillesse, et l'ensemble de tes attentions m'ont accompagné durant toutes ces années. Tu m'as redonné l'envie de battre des ailes lorsque je n'arrivais plus à décoller de la Terre. Nos discussions ont toujours été d'une extrême richesse et ont tant nourri ma réflexion. Mais c'est aussi et surtout à toi que je dois cette merveilleuse et incroyable aventure. Merci pour m'avoir parlé du projet SIRIUS la première fois. Quatre ans plus tard, les cordonnées de cette étoile sont gravées au creux de mon alliance. Aucune page ne serait suffisante pour écrire combien je suis reconnaissante d'avoir eu cette chance et cette opportunité de partager tout ceci avec toi et à quel point la place que tu tiens dans mon cœur est incommensurable ++.

Une profonde reconnaissance à Charles Martin-Krumm qui, au cours de ces trois années, m'a encouragée et motivée. Merci pour tes paroles, tes voyages de pensée et d'avoir été aussi présent. Merci pour m'avoir rappelé qu'il n'y avait « *pas de perf sans stress* », de « *prendre soin* » de moi, qu'il ne fallait pas culpabiliser de ne pas travailler et d'apprendre à dire « *STOP* » si nécessaire. Merci pour tes nombreux conseils aussi bien professionnels que personnels, et pour m'avoir aidé à gravir des montagnes. Merci pour m'avoir souhaité 30 fois mon anniversaire en une journée, pour tes appels, ta disponibilité, tes affronts face à des éditeurs trop présomptueux et ta protection. Tu auras été, je pense, un de mes plus fervents supporters et tu auras toujours une place particulière dans le creux de mon cœur.

Je tiens à remercier le Professeur Henri Marotte pour m'avoir offert l'opportunité de suivre la Capacité de Médecine Aérospatiale (CMA) ou DU de Physiologie Aérospatiale de l'Université paris Cité, anciennement Paris Descartes. J'ai découvert un univers auquel je suis profondément éprise. Merci pour avoir accepté d'être présent en tant que Président du jury de la présente Thèse. Jamais je n'aurai trouvé autant de sens à mon travail que grâce à cette formation. Jamais le désir de voler n'aura été aussi grand. Mes yeux ne cessent de briller pour ce ciel étoilé.

Je tiens à remercier toutes les personnes qui ont rendu ces trois années possibles. Je souhaite exprimer une profonde reconnaissance envers Madame Guillemette Gauquelin-Koch, responsable du pôle Science de la Vie au Centre National des Études Spatiales (CNES) et au Général Emmanuel Gardinetti, responsable du pôle Sciences de l'homme à la Direction Générale de l'Armement (DGA) pour m'avoir offert la possibilité de mener ce doctorat et d'avoir cru en moi. Un profond remerciement à l'Institut de l'Adaptation dont les missions sont portées par Christian Clot et au CHU de Caen représenté par le Dr Stéphane Besnard pour avoir soutenu la plupart des recherches biomédicales réalisées au cours de ces deux dernières années. Merci pour votre soutien à chaque nouveau projet et votre aide lors de la réalisation de ces derniers. Vous avez su avoir foi en moi et à m'accorder le bénéfice du doute alors même que les délais étaient contre nous. Vous avez toute ma reconnaissance et mon respect le plus sincère.

Aussi, je tiens à remercier l'ensemble des personnes qui de près ou de loin ont contribué à ce travail de Thèse. Merci pour votre investissement, votre motivation et vos réflexions. Merci pour avoir été présents à mes côtés. Le travail d'un seul homme n'a pas de sens sans toute l'équipe qui l'entoure. A cette occasion, je tiens tout particulièrement à remercier l'ensemble des équipes qui nous ont accompagné durant nos expérimentations. Sans eux, ce travail n'aurait pas vocation d'être. Je remercie par la même occasion l'Unité de Neurophysiologie du Stress de l'Institut de Recherche Biomédicale des Armées (IRBA) pour leur accueil au cours de ces dernières années. Merci à Damien Claverie pour son aide sur de multiples projets et sa patience face à des électrocardiogrammes trop présomptueux. Je ne saurais assez remercier Sandrine Jacob pour m'avoir aidée à formaliser les données de nombreux projets de recherche et pour m'avoir soutenue lors de ma dernière recherche. Ta joie de vivre et ton sourire sont une véritable bouffée d'air frais.

Je tiens également à remercier le club de l'amygdale qui s'est envolé en microgravité en octobre 2022. Nous avons vécu une semaine riche en expérience et en émotion. Ce dernier restera soudé pour l'éternité.

Je remercie Ellemarije Altena qui a su m'accorder sa confiance depuis déjà de nombreuses années et pour m'avoir permis de mener à bien plusieurs travaux de recherche. Merci pour les opportunités créées et pour notre collaboration resserrée.

Je tiens à remercier l'ensemble des sujets qui ont pris part aux recherches de ce travail de Thèse. Cet engagement, cette détermination et cette dévotion pour la science sont si précieux. Je ne pourrai jamais assez vous remercier pour les heures que vous m'avez accordés. Votre confiance et votre dévouement sont d'une valeur inestimable. Sans vous ce travail n'aurait pas vocation d'être. Merci aux pilotes de chasse Lyche, Serge, Wiki, Beep, Glo, Tiff pour m'avoir accordée leur confiance et suivie lors de la 81ème campagne de vols organisée par l'Agence spatiale européenne en gravité partielle. Un remerciement tout particulier au Dr Céline Dupin, médecin sur la base Antarctique française de Dumont d'Urville qui durant un an a recueilli l'ensemble des mesures psychophysiologiques et sensorielles sur les hivernants. Merci pour cette attention toute particulière qui revient de l'autre bout de la Terre.

Je remercie l'ensemble des médecins de la promotion CMA 2022. J'ai pu trouver une oasis, une place que j'ai longtemps cherchée. Nos longs échanges furent d'une grande richesse intellectuelle, mais j'ai aussi passé d'excellents moments d'après cours. Vous êtes tous incroyables. Je m'envolerai jusqu'à perdre ma fonction ventilatoire avec vous. A cette occasion, merci à Raphaëlle pour avoir accepté de voler lors de la 79ème campagne de vols paraboliques en microgravité de l'Agence Spatiale Européenne (ESA) et pour m'avoir transmis cette passion pour l'aviation. Je reste déterminée à obtenir la licence de planeur. Je tiens aussi à remercier Laurent pour cette passion commune pour la vie hors des frontières terrestres et pour cet amour des astronautes, des voyages et de la nourriture.

Nous avons volé en microgravité ensemble, notre trek en Guyane en allant de Kourou à la jungle nous attend toujours.

Je remercie Frank et Pierre, pilotes AirFrance qui m'ont fait vivre une des plus belles expériences de ma vie en m'ouvrant l'accès au cockpit durant le Vol Paris-Marseille du 6 mai 2022. J'ai vécu une expérience tant humaine que pratique très riche. Grâce à eux, mon DU de Physiologie aérospatiale n'en fut que mieux illustré.

Un profond remerciement aux personnes qui m'entourent.

A cet égard, je remercie sincèrement Jérémy Rabineau pour nos riches échanges, nos expériences de pensée et nos missions communes. Merci pour m'avoir envoyé une carte des terres australes française, elle restera un souvenir unique de l'étude ISHOW. Je suis persuadée que tu iras loin et que tu toucheras les étoiles du bout de tes doigts. Nous avons volé en microgravité ensemble et nous sommes partis de l'autre côté de l'Océan Pacifique lors d'une mission de simulation à la vie sur Mars. Je nous souhaite que cette amitié soit longue et étoilée. J'ai trouvé avec toi ce partage d'une passion pour la vie dans l'espace qui nous anime au quotidien mais également une passion pour les mêmes plaisirs de la vie. Je t'attends toujours pour faire ce marathon des meilleures adresses de Paris. Nous parlons un langage commun et je souhaite que notre pacte de réaliser ensemble un vol en orbite se concrétise.

Merci à cette petite team de thésardes « Entre Nous » pour vos nombreux conseils qui ont nourri ma pensée et mon cœur dans les moments où j'en avais le plus besoin. Vous avez été un moteur dans bon nombre de situations et je n'oublierai pas votre soutien en fin de parcours.

Merci à Adèle Gille pour ton aide lors du recueil de données de ma dernière étude. J'ai passé avec toi des moments riches en émotions, en partage, en échange de pensées. Tu es un petit bout extraordinaire. Prends confiance en tes capacités car tu iras très loin.

Merci à Camille Jégo pour son soutien lors de la dernière ligne droite de la Thèse. Tes e-mails du Nord-Ouest furent une bouffée d'air frais à l'air parisien. Je ne peux que te souhaiter une belle fin de Thèse.

Un sincère merci à Marylou Le Roy qui est devenue ma belle-sœur au cours de ma deuxième année de Thèse. Merci pour ton soutien indéfectible et tes nombreux conseils. Merci pour m'avoir aidée en fin de marathon, pour m'avoir protégée de certains sujets d'étude intenses, et pour m'avoir apporté un grand soutien. Ta compréhension pour avoir vécu toi-même une Thèse a été très précieuse dans les périodes les plus difficiles et par lesquelles, tu es aussi passée. Tu feras une merveilleuse tata.

Merci à Guillaume Michel pour nos discussions si riches sur la place de l'espèce humaine dans l'environnement et en quoi la physiologie ne fait nécessairement sens avec l'aspect de certains concepts théoriques (e.g., merci à l'implication du réflexe auriculo-contontigaire dans les afférences sensorielles). Nos soirées cuisine n'auront jamais été aussi fructueuses. Merci pour avoir passé une heure à chercher des volontaires pour me venir en aide. Je t'en suis très reconnaissante.

Merci à Alexia Ostyn, Mélanie Guillou, Cindy Tidas, Marion Marchand pour m'avoir suivie dans toutes les adresses de brunchs possibles et inimaginables. J'ai retrouvé mes meilleures amies de l'école primaire après tant d'années de soupire, développé une amitié sincère familiale et j'ai formé une nouvelle amitié de la manière des plus insolites qu'il soit. Vous m'avez permis de me ressourcer, de me changer de la Thèse mais aussi de m'écouter sans relâche raconter l'ensemble de mes expériences et de me rendre toujours plus vivante.

Merci à Morgane Rogiers, ma foodie, mon aventurière téméraire. Je te remercie pour ton soutien quotidien. Tu es formidable alors prends confiance en toi et découvre ta propre voie. La réussite est à la portée de tes mains.

Merci à Anouche Banikyan pour avoir accepté que je m'assois le jour de la rentrée de septembre 2017 sur cette place encore disponible. Nous discutions un mois plus tard avec humour et légèreté que nous finirons en doctorat et à l'étranger. Six mois plus tard nous nous envolions vers le Canada pour notre stage, cinq and plus tard tu étais à mes côtés lors de mon mariage et six ans plus tard, je rédige ces lignes. J'ai grandi à tes côtés, je suis devenue confiante dans la beauté des expériences de vie et j'ai appris à oser laisser exprimer ma créativité et mes rêves.

Merci Mamie et Philippe pour votre amour et avoir compris les enjeux de la fin de Thèse. Je n'oublierai pas cet appel dans lequel vous m'avez offert votre aide et soutien émotionnel aux trois-quarts du chemin parcouru. Ces phrases resteront gravées à jamais dans ma mémoire.

Merci à mes beaux-parents pour leurs conseils si précieux. Vous m'avez ouvert les portes de chez vous, apporté un socle identitaire, et de nombreux encouragements durant ces trois années. Vous avez su être à l'écoute et bienveillants envers l'ensemble de mes projets. Merci pour vos attentions dans les moments les plus difficiles. Je ne vous remercierai jamais assez pour votre présence et votre place dans ma vie.

Merci à mon *Tauraron Hamada*. Aucune encre ne serait suffisante pour t'exprimer ma reconnaissance et mon amour. Tu es le pilier qui me soutient et me donne tant. Merci pour tes innombrables heures passées à m'écouter, me relire, à me conseiller, à m'orienter jusqu'à aller endosser le rôle de chercheur. Tout ce que contient cette Thèse n'aurait pu voir le jour sans toi : *Ina mafarkin binciko wannan jeji da kuke magana da yawa, na bacewa a ciki da jin wannan kyawun shiru (« Je rêve d'explorer ce désert dont tu parles tant, de m'y perdre et de ressentir cette beauté silencieuse* »).

Merci à l'ensemble de mes proches dont je n'ai pu citer le nom mais à qui je pense.

Enfin, je ne pourrais exprimer mon immense reconnaissance envers celui qui est devenu mon mari le 25 juin 2022, Mathieu Le Roy, mon *Megheti*. Tu as toujours été à mes côtés, à m'écouter et à tant me donner avec amour et bienveillance malgré mes heures à travailler et mes innombrables paraboles émotionnelles. Merci pour ces nuits à être resté à mes côtés alors que je devais travailler. Merci pour avoir déjoué les codes les plus réfractaires, pour t'être prêté au jeu de la recherche et pour tes réflexions scientifiques stellaires. Merci infiniment pour avoir été présent peu importe les difficultés, pour avoir souhaité me rendre la vie plus facile, et pour l'ensemble de ton aide lors de cette fin de Thèse. Tu as été mon homéostasie durant toutes ces années et c'est aussi grâce à toi j'en suis là aujourd'hui. Une nouvelle aventure nous attend désormais. Je ne peux qu'espérer transmettre notre passion pour l'Univers à notre Ohana.

Je dédie cette Thèse à toutes les futures générations, vous êtes l'avenir.

Tableaux

Figures

Photographies

Curriculum vitae

BARBARA LE ROY

PHD SCIENCES DE LA VIE & DE LA SANTÉ

A 28 ans, je suis passionnée par l'étude de l'impact du milieu spatial sur la santé, en particulier à visée des prochaines longues missions spatiales. Mon profil multidisciplinaire est un gage de la qualité de mes travaux

EXPÉRIENCES

PhD Santé & comportements humains — OCTOBRE 2020 - DÉCEMBRE 2023
CNES (Paris, France), DGA (Paris, France), IRBA (Brétigny, France)

Thèse de doctorat sur l'étude de (1) l'impact des environnements analogues à l'espace sur l'adaptation des prochains équipages, (2) l'identification de profils d'adaptation au moyen de l'IA et la mise en place de contre-mesures

Vice Présidente — MARCH 2023 - MARCH 2025
SEDS France (Paris, France)

Partage des tâches de la direction de SEDS France avec les présidentes & responsable de l'organisation des évènements et partenariats

Médiation sceintifique — OCTOBER 2020 - OCTOBER 2023
ESERO (Agence Spatiale Européenne, France)

Présentations scientifiques sur les analogues spatiaux, la conquête spatiale, la santé des astronautes

Ingénieur cogniticienne — MARS 2020 - SEPTEMBRE 2020
VirtualiSurg (Paris, France)

Mise en place d'un protocole d'expérimentation auprès d'internes en chirurgie afin d'évaluer l'acquisition de compétences favorisées par l'utilisation d'un simulateur en réalité virtuelle en chirurgie mini-invasive (HRV, questionnaires, capteurs de posture)

Stage en laboratoire de recherche — JANVIER - JUILLET 2019
IRBA (Brétigny, France), Unité Neurophysiologie du stress

Recrutement, mise en place d'un protocole expérimental, passation, analyse des données psychométriques et physiologiques (HRV, GSR, respiration) pour étudier la régulation émotionnelle selon le profil d'empathie

COMPÉTENCES

- Sciences cognitives, neurosciences, neurophysiologie, physiologie, psychologie & ergonomie cognitive appliqués aux environnements analogues (ICE/EUE) et à la prévention des risques ;
- Expertise médicale en médecine aéronautique (i.e., prévention du risque hypoxique, maladie de décompression d'altitude, physique des gaz, thermorégulation du corps, ingénieurie des systèmes d'oxygène embarqués, aptitudes médicales des cl 1, 2 et 3) & réglementation aéronautique ;
- Algorithmes de machine learning & deep learning (i.e., apprentissage supervisé et non supervisé) ;
- Capteurs de mouvements (RealSens, Mocap), estimation de pose (OpenPose), reconnaissance de geste (GMM, HMM, HHMM), sonification & analyse du geste ;
- Méthodes d'évaluation centrées utilisateurs & méthodes de conception (UX/UI) ;
- Data science (analyses statistiques standards, bayésiennes et approfondies) ;
- Programmation informatique en langage Python, R & Max ;
- Réalité virtuelle, augmentée et mixte (Unity, Wings 3D) ;
- Accessibilité & technologies du handicap, IoT ;
- Mise en place de protocole expérimental, rédaction de rapports & articles scientifiques, comité de protection des personnes ;
- Design graphique (i.e., Canva) ;
- Utilisation des supports numériques (B2i, C2i, pack office, Macintosh)

CONTACT

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ÉDUCATION

2020 - 2023
Université de Lorraine (APEMAC)
Doctorat Sciences de la vie et de la santé

2021 - 2022
Université de Paris Descartes
DU Physiologie et Ergonomie Aérospatiale (Capacité Médecine Aéro) mention Très Bien

2019 - 2020
École Mines ParisTech
Master Spécialisé Intelligence Artificielle et Mouvement dans les Industries et la Création mention Très Bien

2017 - 2019
Université de Bordeaux
Master Sciences cognitives et Ergonomie mention Bien

2017
Croix-Rouge Française
PSC 1

LANGUES

- Français ●●●●●
- Anglais ●●●●○
- Espagnol ●●●○○

CONFÉRENCES

Journées scientifiques IRBA AVRIL 2023
Brétigny-sur-Orge, France

Présentation orale
Des environnements isolés et confinés au défi spatial: Étude des relations entre sensorialité et adaptation au stress

World Extreme Medicine Conference OCTOBRE 2022
Edimburgh, Ecosse

Présentation orale
Survival in extreme waters

Int Conference of Aerospace Medicine SEPTEMBRE 2022
Paris, France

Présentation orale
PRISMA review on ICE/EUE environment

Journées scientifiques CNES SEPTEMBRE 2022
Toulouse, France

E-poster & présentation
Des environnements isolés et confinés au défi spatial: Étude des relations entre sensorialité et adaptation au stress

Congrès Santé & Espace MARS 2022
Marseille, France

Partenariats avec les acteurs du spatial dans les régions PACA et Alpes-Maritimes tables rondes

Int Conference on Medicine in Extreme Environment JUILLET 2021
Paris, France

Session « Medical and Health Sciences »
Cardiac Biosignal and Adaptation in Confined Nuclear Submarine Patrol

Int Positive Psychology Association JUILLET 2021
Virtuel

E-poster présentation
Sub-Surface Confinement: Evidence from Submariners of the Benefits of Being Mindful

Congrès Français et Francophone de Psychologie Positive JUIN 2021
Virtuel

Présentation Symposium Santé
Cardiac biology and adaptation on a nuclear submarine patrol

MÉDIATION

2022
Ma thèse en 180 secondes
Finale régionale du 10 mars 2022

2021
DAAD Science Slam Paris
Prix du public

2021-2023
ESERO (Mission X)
Vulgarisation scientifique sous forme de conférences et ateliers auprès des établissements scolaires (i.e., maternelle, primaire, collège) et d'hôpitaux (i.e., service de pédiatrie)

2021
IPPA
Membre actif

TUTORAT

2023
Projet ENACT g+
Management d'équipe pour une recherche visant à étudier l'impact des changements répétés de gravité lunaire et martienne sur la cognition et le sommeil de pilotes de chasse

2022
Projet ENACT 0g
Management d'équipe pour une recherche visant à étudier l'impact des changements répétés de microgravité pour le tourisme spatial

2022
Projet RADL'Ô
Management d'équipe pour une recherche visant à étudier l'impact de 5 jours de survie en mer sur les capacités psycho-physio-sensorielles et cognitives

2022
Projet ANTIDOTE
Encadrement de deux étudiantes de master dans le cadre d'un projet de recherche sur l'impact d'un exercise en situation NRBC des Pompiers de Paris sur la variabilité de fréquence cardiaque d'un opérateur

2021
Projet Bataclan
Encadrement d'un interne en médecine militaire sur l'analyse de données d'une étude visant à définir des facteurs prédictifs de développement d'un état de stress post traumatique suite aux attentats du 13 novembre 2015

2021
Projet SEREINE
Encadrement d'une étudiante de master sur l'analyse de données d'une étude visant à mettre en place un algorithme de clustering dans le cadre de la prévention de la dépression post partum

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Lefranc, B., Martin-Krumm, C., Aufauvre-Poupon, C., Berthail, B., & Trousselard, M. (2020). Mindfulness, Interoception, and Olfaction: A Network Approach. *Brain sciences*, *10*(12), 921. https://doi.org/10.3390/brainsci10120921.

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Giaume, L., Le Roy, B., Jost, D., Lauga-Cami, H., Travers, S., & Trousselard, M. The effects of chemical, nuclear, radiological medical training on first responders: dysfunctional heart rate variability leads to altered physiological and psychological response (à soumettre).

Le Roy, B., Martin-Krumm, C., Aufauvre-Poupon, C., Vannier, A., Mercier, C., Delas, Y., & Trousselard, M. What role can hope play in extreme, isolated and/or confined environments? (à soumettre).

Nomenclature

$\alpha1$: detrended fluctuation analysis self-similarity parameter that represented short-term fluctuations ; paramètre d'autosimilarité de l'analyse des fluctuations tendancielles représentant les fluctuations à court terme

$\alpha2$: detrended fluctuation analysis self-similarity parameter that represented long-term fluctuations ; paramètre d'autosimilarité de l'analyse des fluctuations tendancielles qui représente les fluctuations à long terme

1CRRT : one choice releasing reaction time ; temps de reaction à un choix

2CRRT : two simultaneous choices releasing reaction time ; temps de reaction à deux choix simultanés

A : appetite ; appétit

ABVN : auricular branch of the vagus nerve ; branche auriculaire du nerf vague

AD-ACL : activation-deactivation adjective checklist ; liste des adjectifs d'activation et de désactivation

ADAC : activation-deactivation adjective checklist ; liste des adjectifs d'activation et de désactivation

ACT : acceptance commitment therapy ; thérapie d’engagement et d’acceptation

AI : artificial intelligence ; intelligence artificielle

AIEQ : addictive intensity evaluation questionnaire ; questionnaire d'évaluation de l'intensité de la dépendance

ANS : autonomous nervous system ; système nerveux autonome

APTICE : augmented physical training for isolated and confined environments ; entraînement physique augmenté pour les environnements isolés et confinés

BDNF : blood brain derived neurotrophic factor ; facteur neurotrophique dérivé du cerveau

BF : bayesian factor ; facteur bayésien

CBRN : chemical, biological, radiological and nuclear ; nucléaire, radiologique, biologique, et chimique

CELSS : controlled ecological life support system ; système écologique contrôlé de maintien de la vie

CFS : coping flexibility scale ; echelle de flexibilité cognitive

CI : confidence intervals ; intervalles de confiance

CNES : french space agency ; centre national des études spatiales

CNS: central nervous system ; système nerveux central

CoP : centre of pressure ; centre de pression

CS : correlation stability ; stabilité de la corrélation

CSS : china space station ; station spatiale chinoise

DBT : dialectical behavior therapy ; thérapie comportementale dialectique

DDU : Dumont d'Urville station ; station Dumont d'Urville

DyNaChron : chronic nasal dysfunction ; dysfonctionnement nasal chronique

EA : energetic arousal ; activation générale

EduFlow : educational flow questionnaire ; questionnaire sur le flow dans l'éducation

EBIC : extended bayesian information criterion ; critère d'information bayésien étendu

EBP : evidenced based practice ; pratique fondée sur des données probantes

ECG : Eeectrocardiogram ; electrocardiogram me

ERP : event-related potential ; potentiel lié à l'événement

ES : executive speed ; vitesse d'exécution

ESA : european space agency ; agence spatiale européenne

ETOC : european test of olfactory capabilities ; test européen des capacités olfactives

EUE : extreme and unusual environment ; environnement extreme et inhabituel

EVA : extra-vehicular activity ; sortie exta-vvéhiculaire

FMI : freiburg mindfulness inventory ; inventaire de pleine conscience de freiburg

fMRI : functional magnetic resonance imaging ; imagerie par resonance magnétique fonctionnelle

FN: false negative ; faux négatif

FP : false positive ; faux positif

GAS : general adaptation syndrome ; syndrome d'adaptation général

GENIAL : genomics, environment, vagus nerve, social interaction, allostatic regulation, and longevity model ; modèle de génomique, d'environnement, du nerf vague, d'interaction sociale, de régulation allostatique et de longévité

GHQ : general heath questionnaire ; questionnaire de santé général

GLASSO : group least absolute shrinkage and selection operator ; opérateur de sélection et de moindre rétrécissement absolu du groupe

GRADE : grading of recommendations assessment, development and evaluation ; gradation de l'évaluation, du développement et de l'évaluation des recommandations

GUT : generalized unsafety theory ; non-sécurité généralisée du stress

HERA : human exploration space analog ; analogue de l'espace pour la recherche humaine

HI-SEAS : hawaii space exploration analog and simulation ; simulation et analogue de l'exploration spatiale à hawaii

HF : high frequency ; haute fréquence

HN : very limited or no existence of minor non-psychiatric or psychotic disorders ; existence très limitée ou inexistante de troubles mineurs non psychiatriques ou psychotiques

HPA : hypothalamic- pituitary-adrenocortical ; hypothalamique-hypophysaire-adrénalien

HPa : high parasympathetic activity ; activité parasympathique élevée

HPd : high parasympathetic delta ; delta parasympathqiue élevé

HR: hear rate ; fréquence cardiaque

HRV : heart rate variability ; variabilité de la fréquence cardiaque

ICE : isolated and confined environment ; environnement isolé et confiné

IPEV : paul emile victor institute ; institut paul émile victor

ISS : international space station ; station spatiale international

iVNS: invasive vagus nerve stimulation ; stimulation du nerf vague invasive

LASSO : least absolute shrinkage and selection operator ; opérateur de sélection et de moindre rétrécissement absolu

LDL : loudness discomfort level ; seuil d'inconfort auditif

LDSE : long duration space flight ; vols spatiaux de longue durée

LEEDS : leeds sleep evaluation questionnaire ; questionnaire d'évaluation du sommeil leeds

LF : low frequency ; basse fréquence

LPa : low parasympathetic activity ; faible activité parasympathique

LPd: low parasympathetic delta ; faible delta parasympathique

LSS : life support systems ; systèmes de support vie

MAIA : multidimensional assessment of interoceptive awareness ; évaluation multidimensionnelle de la conscience intéroceptive

MBAT : mindfulness-based attention training ; entraînement à l'attention basé sur la pleine conscience

MBCT : mindfulness-based cognitive therapy ; thérapie cognitive basée sur la pleine conscience

MBSR : mindfulness-based stress reduction ; réduction du stress basée sur la pleine conscience

MD : mindfulness disposition ; disposition mindful

MMFT : mindfulness-based mind fitness training ; entraînement à la santé mentale basé sur la pleine conscience

NAMT : neurofeedback-augmented mindfulness training task ; tâche d'entraînement à la pleine conscience renforcée par le neurofeedback

NaN : missing values ; valeurs manquantes

NASA : national aeronautics and space administration ; agence spatiale américaine

NEEMO : NASA extreme environment mission operations ; opérations de mission en environnement extrême de la NASA

NOAA : national oceanic and atmospheric administration ; administration nationale des océans et de l'atmosphère

NRD : dorsal raphe nucleus ; noyau du raphé dorsal

NTS : nucleus tractus solitarius ; noyau du tractus solitaire

OR : standard values for non-psychiatric or minor psychotic disorders within the general population ; valeurs standards pour les troubles non psychiatriques ou psychotiques mineurs dans la population générale

PBWE : positive built workplace environment ; environnement de travail positif et construit

PCA : principal component analysis ; analyse en composante principale

PESS : personal evaluation of six senses : évaluation personnelle des six sens

PFC : prefrontal cortex ; cortex préfrontal

PHS : personal hierarchical sensory ; hiérarchie personnelle des sens

pNN50 : percentage of adjacent NN intervals that differ from each other by more than 50 ms ; pourcentage d'intervalles NN adjacents qui diffèrent les uns des autres de plus de 50 ms

PNRA : national antarctic research program ; programme national italien de recherche en Antarctique

PNS : parasympathetic nervous system ; système nerveux parasympathique

PPE : protective personal equipment ; équipement de protection personnel

PQ-f : presence questionnaire ; questionnaire de présence

PRISMA : preferred reporting items for systematic reviews and meta-analyses ; éléments de rapport préférés pour les revues systématiques et les méta-analyses

PSS : perceived stress scale ; échelle de stress perçu

PTSD : post-traumatic stress disorder ; état de stress post-traumatique

PTT : pure tone testing ; test de tonalite pure

RD : reaction to difficulty ; reaction à la difficulté

RMSSD : root mean square of differences between adjacent RR intervals ; moyenne quadratique des differences successives entre intervalles RR adjacents

RR : successive variation of the intervals between two heartbeats ; variabition successive des intervalles entre deux battements de coeur

RRT : releasing reaction time task ; tâche de relâchement du temps de réaction

RT : reaction time ; temps de réaction

RTE : relative treatment effect ; effet relative du traitement

SA : sensory acuity ; acuité sensorielle

SAD : subsyndromal seasonal affective disorder ; trouble affectif saisonnier subsyndromal

SampEn : sample entropy ; entropy d'échantillonnage

SbQ : socio-biographical Questionnaire ; questionnaire socio-briographique

SD1 : standard deviation of instantaneous short-term RR variability ; deviation standard de la variabilité instantannée des intervalles RR à court terme

SD2 : standard deviation of continuous long-term RR variability ; deviation standard de la variabilité continue des intervalles RR à long terme

SIRIUS : scientific international research in a unique terrestrial station ; recherche scientifique international dans une station terrestre unique

SDNN : standard deviation of normal-to-normal RR interval ; deviation standard de l'intervalle RR

SGI : sensory gating inventory ; inventaire des canaux sensoriels

SMMGC : standard model of military group cohesion ; model standard de cohesion de groupe militaire

SNS : sympathetic nervous system ; système nerveux sympathique

SPANE : scale of positive and negative experience ; échelle des experiences positives et négatives

SRT : simple reaction time ; temps de réaction simple

SSBN : sub-surface ballistic nuclear-powered missile submarines ; sous-marin nucléaire lanceur d'engins

SSQ : simulator sickness questionnaire ; questionnaire sur les cybermalaises

SVM : support vector machine ; machine à vecteurs de support

TA : tense arousal ; activation élevée

taVNS : transcutaneous auricular vagus nerve stimulation ; stimulation transcutannée auriculaire du nerf vague

TN: true negative ; vrai négatif

TP: true positive ; vrai positif

UX : user experience ; expérience utilisateur

VAS : visual analogue scale ; échelle analogue visuelle

vmPFC : ventromedial prefrontal cortex ; cortex préfrontal ventromédian

VN : vagus nerve ; nerf vague

VNS : vagus nerve stimulation ; stimulation du nerf vague

VR : virtual reality ; réalité virtuelle

VRET : virtual reality exposure therapy ; thérapies d'exposition à la réalité virtuelle

TABLE DES MATIERES

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MEN WALK ON MOON

ASTRONAUTS LAND ON PLAIN; COLLECT ROCKS, PLANT FLAG

AVANT-PROPOS

Il est inutile de revenir à Icare
pour montrer que le désir de voler
a toujours été très grand chez l'homme.
Mais voler pour imiter l'oiseau est une chose
et quitter la Terre pour aller « ailleurs » en
est une autre. Dans les deux cas existe une
même nécessité, se libérer de la pesanteur,
mais dans le second le fait de ne plus dépendre
de l'attraction terrestre revêt une autre dimension,
celle d'une migration hors de notre atmosphère,
devenir, au moins pour un temps, un extraterrestre
dans le sens littéral du mot

Rivolier, 1997. p.15

Au plus près du plus grand voyage de notre temps, de nombreuses questions restent en suspens obligeant l'espèce humaine à repenser sa place dans l'Univers. Notre Terre, planète ô combien bleue, a accueilli les prémisses de l'humanité il y a près de 4 millions d'années, et y offre depuis un espace de vie et de développement. A l'aube des prochains longs voyages dans l'espace, explorer l'inexplorable n'a jamais été aussi présent. De tout temps, l'être humain a été animé par l'ambition de progresser tant sur le plan scientifique que technique, repoussant ses limites au-delà du possible. A une époque, il s'agissait d'explorer la Terre en naviguant durant des mois sur des bateaux à voiles. L'exploration des terres de glace a ensuite pris place dans les pôles confrontant les hommes à des conditions climatiques jusqu'alors jamais ressenties. Mais depuis la nuit des temps, la voûte céleste constitue un objet d'émerveillement vers lequel tendre pour se rapprocher un peu plus près des étoiles (Photographie 1). L'espace, aussi mystérieux qu'envoûtant, a cette force d'attraction des choses inaccessibles qui poussent l'humanité à s'y engager avec passion.

Photographie 1
Image de la planète bleue plus communément appelée Terre et baptisée « Earthrise ».
Photographiée par l'équipage Apollo 8 en 1968.

Toutes les routes empruntées par ces explorateurs sont autant de voies vers un but de connaissances, de compréhension et de découvertes. Tous ont dû surmonter des mirages où parfois le doute, plus fréquemment que l'expérience de mort imminente, venait les hanter jusqu'à les perdre. Sommes-nous assez dignes pour expérimenter une telle beauté ? Est-ce que l'Être Humain est à la hauteur pour y arriver ? Sommes-nous assez courageux pour affronter le risque accru de mort accidentelle ? Autant de questions qui sont sans réponse mais pour autant fondamentales ; plus encore à l'heure actuelle où la colonisation de l'espace intéresse de nombreuses nations. Le doute reste une arme pour combattre et cheminer vers les milieux les plus hostiles de la planète. Oui, dès les premiers instants de questionnement, nous sommes déjà en train de trouver des stratégies d'adaptation pour nous permettre d'affronter le passé, le présent et le futur et de les communiquer pour que le voyage vers l'espace avance.

Le désir de voler a de tout temps bercé l'humanité. En passant par Icare, Louis Blériot, Antoine de Saint-Exupéry, Youri Gagarine, Neil Armstrong, ou Thomas Pesquet, tous ont rêvé de se hisser au-delà de la gravité terrestre. Certains auront fait de ce rêve une réalité en allant aux abords de la Terre, sur la Lune et jusqu'à créer une station spatiale internationale (*international space station*, ISS) qui depuis 2001 reste en perpétuelle habitation. Ces progrès nous ont permis de côtoyer et de nous adapter à un environnement hostile.

Les recherches scientifiques nous ont permis de mieux comprendre dans quelle mesure un individu y est à minima capable d'acclimatation et d'adaptation[1]. Ainsi, Christian Clot[2] aura traversé les quatre milieux les plus hostiles de la planète. Véritable explorateur des temps modernes, il donne un tout autre sens à ce que « explorer » signifie en déployant des méthodologies de terrain pour ramener de la connaissance sur les possibilités d'adaptation de l'espèce humaine. Tant d'autres avant lui se sont risqués sur les monts en Patagonie, en forêt amazonienne, dans les froids les plus secs de Sibérie en

[1] L'acclimatation et l'adaptation sont deux mécanismes évolutifs différents. L'acclimatation est un terme issu de la physiologie. Il concerne les changements physiologiques, biochimiques, anatomiques chez un individu à l'issue de l'exposition à un nouvel environnement. Ces derniers sont souvent réversibles dans le temps. L'adaptation est un terme issu de la psychologie. Il fait référence au concept même d'évolution de l'espèce et donc de sélection naturelle en cherchant la probabilité de survie d'un individu. Les modifications entraînées sont quant à elles irréversibles dans le temps (e.g., génome).

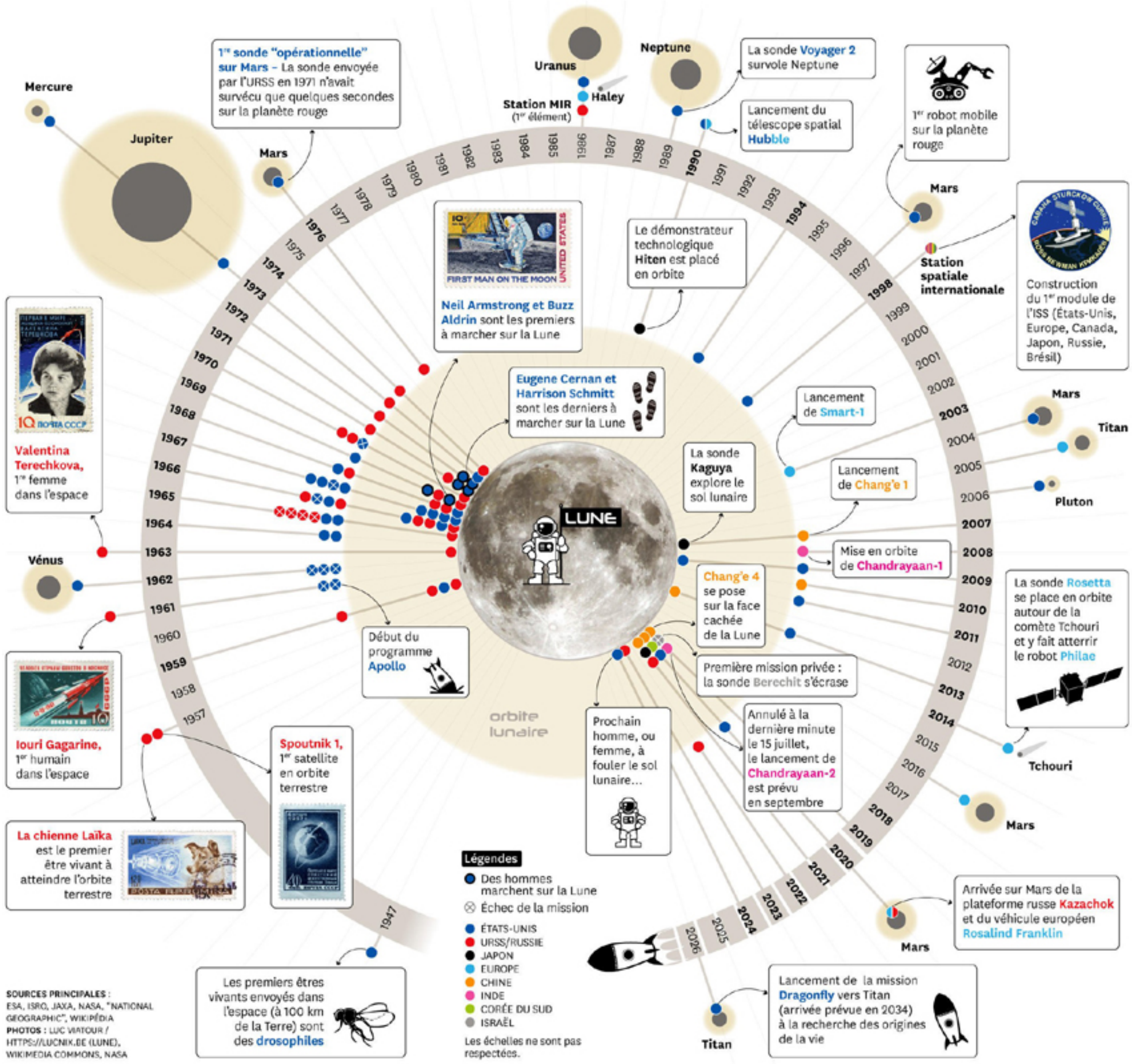
[2] Christian Clot est un explorateur et un chercheur franco-suisse ayant à cœur de mieux comprendre comment l'espèce humaine est capable d'adaptation. Fondateur de l'Institut de recherche sur l'Adaptation « Human Adaptation Group » et du groupe « The Adaptation group », le partage des connaissances acquises à travers les expéditions est le *leitmotiv* de ses projets. Il parcourt les milieux les plus extrêmes de la planète afin d'apporter des réponses concrètes, coordonnées par la recherche scientifique, dont les résultats auront des répercussions sans précédent quant à l'avenir écologique de la Terre mais aussi face aux prochains voyages spatiaux. En somme, il a pour vocation de préparer l'être humain au monde de demain.

passant par la glace de l'Antarctique. Autant de milieux, qui ont permis de découvrir des terrains jusqu'alors inhabités, de nouvelles formes de vie qu'elles soient humaines, animales ou bactériennes mais également des moyens de faire face à l'isolement, au confinement comme à l'immensité, à l'inhabituel, à l'extrême.

Pour autant, lorsque le président des États-Unis John F. Kennedy a pris la parole en mai 1961 en réponse au premier vol orbital américain de l'astronaute Alan Shepard le 5 mai de la même année, il s'est engagé à « envoyer des hommes sur la Lune et à les ramener sains et saufs sur Terre au cours de la décennie ». A cette date, personne ne connaissait les effets des vols spatiaux sur l'être humain en tant que « corps de chair ». Il y avait là aussi plus de questions que de réponses que ce soit sur les effets de l'accélération, de la pression, de la concentration de CO2, des radiations, ou encore de la microgravité. Le challenge qu'avaient choisi de relever les États-Unis était incroyablement grand. Le risque entrepris était immense, la sécurité des astronautes mise à rude épreuve pour que de futurs astronautes puissent habiter une ISS avec une meilleure connaissance des conséquences de ces missions habitées. Dans les suites de ce voyage sur la lune, le National aeronotics and space act a créé le 29 juillet 1958 l'Agence spatiale américaine (*National aeronautics and space administration*, NASA), pour planifier, diriger, superviser et soutenir les activités civiles américaines de vol spatial, y compris les vols habités. La Figure 1 a pour volonté de retracer de manière exhaustive la conquête spatiale de 1957 à nos jours.

Figure 1

Conquête spatiale de 1957 à nos jours, réalisée par Catherine Doutey et Carole Lembezat du Courrier International



Du premier homme dans l'espace à une station habitée

Le programme Mercury (1958-1963), premier programme spatial américain d'une durée de 2 jours 5 heures 55 minutes et 33 secondes, a exposé deux astronautes à des vols suborbitaux de 15 minutes, puis quatre astronautes à des vols orbitaux d'environ 5 à 34 heures. En parallèle, le programme russe Vostok (1961-1963) a vu six vols d'une durée cumulée de 15 jours 22 heures 21 minutes. Ce dernier avait pour vocation de mettre en orbite un vaisseau habité par un astronaute. Le programme Gemini (1964-1966) a quant à lui exposé 16 astronautes à 10 vols orbitaux cumulant une durée de 40 jours 9 heures 51 minutes et 46 secondes. Ce programme a préparé le terrain du futur programme Apollo (1961-1972). Ce dernier a eu pour vocation d'aller déposer le premier homme sur la Lune et cumula onze vols, deux (Apollo 7 et 9) en orbite terrestre et huit (Apollo 8, 10, 11, 12, 14 à 17) en orbite lunaire d'une durée de 104 jours 64 heures 0 minutes et 37 secondes. Avec si peu d'expositions aux vols spatiaux, les scientifiques ne savaient pas si les effets observés sur les astronautes tant physiques (e.g., hypervolémie globale entraînant une des modifications cardio-vasculaires) que psychiques (e.g., troubles de l'humeur, hallucinations) étaient des réactions individuelles ou des réactions communes, et s'ils étaient dus aux vols spatiaux, au confinement et/ou à la microgravité (Berry et al., 2009). Il faudra attendre le 21 juillet 1969 pour que les États-Unis frôlent le sol lunaire avec l'astronaute Neil Armstrong qui prononça dans un élan d'humanité : *« That's one small step for [a] man, one giant leap for mankind »*. Le programme russe Soyouz (1967-1976) a cumulé treize vols d'une durée de 97 jours 0 heure 45 minutes et 44 secondes et avait pour objectif similaire de conduire un cosmonaute soviétique sur la Lune. En effet, initialement les premiers astronautes allant dans le vide spatial ne restaient pas assez longtemps pour que l'on mesure avec les méthodes de l'époque les effets négatifs d'un tel milieu hostile, et ce dans la durée. Ils ne pouvaient qu'en décrire, avec beaucoup de difficulté, le sentiment de magnificence qui les gagnait.

« While I had trained for thousands of hours to immediately dive into the postinsertion checklist, I couldn't overcome the temptation to look at our planet, now filling the forward windows. Blue, white, and black were the only colors. Swirls of lacey clouds patterned an otherwise limitless expanse of deep blue Atlantic Ocean. All of this was framed in a pre-Genesis black. There was no blackness on Earth to compare…not the blackest night, the blackest cave, or the abysmal depths of any sea. To say the view was overwhelmingly beautiful would be an insult to God. There are no human words to capture the magnificence of the Earth seen from orbit. And we astronauts, cursed with our dominant left brains, are woefully incapable of putting in words what the eyes see. But still we try ».

Cet extrait de l'astronaute Mike Mullane (Mullane, 2006 ; p. 473) est issu de la mission STS-41, première mission de la navette spatiale Discovery, qui a duré du 30 août au 5 septembre 1984.

Il poursuivra lors de la mission STS-36 du 28 février au 4 mars 1990.

« *While I had no nausea, I did experience the same painful backache from spine lengthening that I had encountered on STS-41D and 27* » (Mullane, 2006 ; p.904).

L'intérêt de la France pour l'espace est relativement ancien et fait suite à la Seconde Guerre Mondiale. Le 2 août 1961 marque le lancement du premier programme spatial français. Le 19 décembre 1961, la première agence spatiale française voit le jour. Le Centre nationale des études spatiales (*French space agency*, CNES) est officiellement créé. En 1970, le CNES projette d'envoyer le premier astronaute français dans l'espace. Or, que ce soit la France, la Grande-Bretagne ou l'Allemagne, de nombreux défis financiers et technologiques existaient. Ces derniers ont progressivement débouché sur les premiers éléments d'une collaboration durable entre les trois pays. Dans ce contexte, l'Agence spatiale européenne (*European space agence*, ESA) fondée le 31 mai 1975 sous l'impulsion de la France, la Grande-Bretagne et l'Allemagne vise la création d'une agence intergouvernementale qui aurait pour vocation de traiter des projets communs (i.e., étude et exploration de l'Univers ; recherche sur les véhicules spatiaux ; coordination des vols habités ; mise en place d'un GPS européen). Toutefois, aucun astronaute français ne fut sélectionné malgré cinq qualifications lors du programme européen Spacelab en 1977. Spacelab est issu d'une collaboration entre l'ESA et la NASA dont l'objectif était la construction d'un laboratoire spatial en Europe. Cependant, ce programme marque pour l'ESA le début des vols habités avec la sélection de son premier astronaute Ulf Merbold (Allemagne) qui effectuera un vol du 28 novembre au 8 décembre 1983 en tant que premier européen à aller dans l'espace. Il faudra attendre 1982 pour que Jean-Loup Chrétien devienne le premier français et européen non issu du bloc soviétique à s'envoler dans l'espace dans le cadre du programme russe Interkosmos visant des collaborations internationales. Il effectuera trois vols spatiaux : du 25 juin au 2 juillet 1982 (Saliout 7) ; du 26 novembre au 21 décembre 1988 (Mir) ; et du 25 septembre au 5 octobre 1997 (Atlantis). Patrick Baudry, doublure de l'astronaute Jean-Loup Chrétien sera quant à lui envoyé par la NASA dans l'espace du 17 au 24 juin 1985 (Discovery). Ce premier vol vient de décisions politiques, intervenant à la fois dans un climat d'élections présidentielles du côté de la France et du contexte de Guerre Froide entre la Russie et les États-Unis. D'autres astronautes français seront par la suite sélectionnés incluant Jean-Pierre Haigneré qui effectua deux vols spatiaux en 1993 et 1999 (186 jours à bord de Mir) ; Michel Tognini qui effectua également deux vols spatiaux du 22 au 27 juillet 1992 (Mir) et du 22 au 27 juillet 1999 (Mir) ; Jean-François Clervoy qui effectua 3

vols spatiaux en 1994, 1996 (Mir) et 1999 (Discovery, mission sauvetage de Hubble) ; Jean-Jacques Favier qui effectua un vol spatial de juin à juillet 1996 (Columbia).
C'est durant cette période que nait l'ISS. Première station spatiale internationale créée par l'espèce humaine, elle est aujourd'hui le plus grand objet terrestre jamais déployé dans le vide spatial. Située en orbite basse entre 360 et 400 km de la Terre inclinaison à 51.6°, l'ISS est entrée en service le 20 novembre 1998. Chaque jour, les astronautes à son bord peuvent y observer 16 couchers et levers de soleils alternant entre obscurité et rayons du soleil. Claudie André Haigneré est devenue la première femme astronaute française et européenne à aller dans l'espace et à bord de l'ISS en 1996. Elle effectua deux vols spatiaux du 17 août au 2 septembre 1996 (Soyouz TM-23, Mir) et du 21 au 31 octobre 2001 (Soyouz, ISS).

D'autres astronautes se sont envolés dans le cosmos pour stationner à bord de la station Mir ou de l'ISS. Léopold Eyharts qui effectua deux vols spatiaux du 29 janvier 1998 au 18 février 1998 (Soyouz TM-27, Mir) et du 7 février 2008 au 11 mars 2008 (STS-122, ISS) ; et Philippe Perrin qui effectua un vol du 5 au 19 juin 2002 (STS-111). Ces dernières années, l'astronaute français Thomas Pesquet, a rallumé pour beaucoup de Français le regain d'intérêt du grand public pour le milieu spatial. Il a effectué à ce jour deux vols de six mois chacun du 17 novembre 2017 au 2 juin 2017 et du 23 avril 2021 au 8 novembre 2021. Il est devenu le 4 octobre 2021 le premier français commandant de l'ISS et espère être le premier français à poser le pied sur La Lune avant la destination finale Mars. La France est aujourd'hui un acteur majeur de l'ESA parmi les 22 membres étatiques (i.e., l'Allemagne, l'Autriche, la Belgique, le Danemark, l'Espagne, l'Estonie, la Finlande, la France, la Grèce, la Hongrie, l'Irlande, l'Italie, le Luxembourg, la Norvège, les Pays-Bas, la Pologne, le Portugal, la Roumanie, le Royaume-Uni, la Suède, la République Tchèque et la Suisse) qui la composent, dont le siège social se situe à Paris (France).

Un nombre limité d'astronautes ont effectué de longs séjours dans l'espace. En 1987, les astronautes russes Vladimir Titov et Musa Manarov ont passé près de 366 jours à bord de la station spatiale russe Mir. Nom du programme Russe, Shuttle-Mir s'est étalé du 3 février 1994 au 2 juin 1998 pour 11 missions. Placée sur orbite basse le 20 février 1986 (330/360km, inclinaison orbitale 51.6°), la station MIR fut détruite le 23 mars 2001. En 1994, Valeri Polyakov y a passé près de 438 jours, record à l'heure actuelle du plus long séjour de l'homme dans l'espace. Du côté des États-Unis, les programmes Salyut (19 avril 1971-7 février 1991) et Skylab (14 mai 1973-11 juillet 1974) se sont poursuivis avec à leur compte 38 missions pour le premier et 3 missions pour le second. C'est bien l'objectif de l'ISS que d'offrir à la communauté internationale scientifique une base pour mieux comprendre l'environnement hostile de l'espace. Sa mise en route a permis à cet égard d'allonger les durées des missions spatiales à six mois en moyenne. Les astronautes américains Scott Kelly et Mikhail Kornienko ont passé en 2015 près de 346 jours à son bord. Ce séjour a permis de recueillir nombre de données tant psychologiques, physiologiques que neurologiques, dressant un tableau de l'impact des effets à long terme de l'espace sur le corps. Les résultats des études qui se poursuivent les prochaines années seront déterminants pour les prochains longs voyages dans l'espace. Le 6 février 2020, Christina Koch devient la première femme astronaute à détenir le record du plus long séjour dans l'espace pour une femme avec une mission de 328 jours. A ce jour, le record du plus long séjour dans l'espace est détenu par l'astronaute américaine Peggy Whitson qui a cumulé 665 jours. Il s'agit également de la première femme à avoir eu les commandes de l'ISS et ce deux fois. Âgée de 62 ans, elle projette de repartir dans l'espace pour sa première mission privée. L'année 2021 fut marquée par la mise en orbite du premier module de la future station spatiale chinoise (*china space* station, CSS ; « *Tiangong* » en chinois). Sa construction a été terminé le 1er novembre 2022. Le 5 juin 2022, trois taïkonautes dont l'astronaute Jiu Yang (i.e., première femme chinoise à être allée dans l'espace) ont rejoint le « Palais Céleste » pour une durée de six mois dans le cadre de la mission Shenzhou-14. Celle-ci a pour objectif l'assemblage de deux nouveaux modules *Wentian* et *Mengtian* au module de la station centrale *Tianhe*. Cette station pourrait être la seule et unique en orbite basse après le retrait de l'ISS dans les années à venir.

Nouvelle étape ces dernières années avec l'arrivée du tourisme spatial et avec lui, un nombre incommensurable de défis. Le 28 avril 2001, l'homme d'affaire américain Dennis Tito fut le premier touriste spatial à frôler les murs de l'ISS à bord de la mission Soyouz TM-32. Depuis 2021, il y a eu un regain d'intérêt pour ouvrir l'espace au commerce. Les entreprises Blue Origin et Virgin Galactic ont envoyées des touristes vers l'espace suborbital en juillet 2021. Depuis, Blue Origin en est à son cinquième vol au 4 juin 2022 avec l'envoi de six individus pour une durée de 10 minutes au-delà de la frontière de Karman. Les équipages peuvent observer la courbure de la Terre mais n'ont pas jusqu'alors dépassé l'atmosphère terrestre.

Yusaku Maezana, milliardaire japonais accompagné de son assistant Yozo Hiraro, se sont envolés le 8 décembre 2021 pour l'ISS en compagnie des astronautes de la mission Soyouz MS-20. Avant le décollage, Yusaka Maezena déclarait « Je désire vraiment voir la Terre depuis l'espace, avoir l'expérience zéro gravité, de comment l'espace change les gens, de comment moi je vais changer après ce vol[3] ». Leur séjour aura duré douze jours au cours desquels Yasaka Maezena se dit prêt à aller sur la Lune. Dernièrement, un équipage composé de trois touristes et un astronaute a décollé le 9 avril 2022 à bord de la capsule Crew Dragon, propulsée par la fusée Falcon 9 de Space X. La mission intitulée Ax-1 (i.e., pour la première mission d'Axiom) fut intégralement privée et organisée par la société Axiom Space en collaboration avec Space X. Fondée en 2016, Axiom Space dirigée par l'ancien responsable de la NASA Michael Suffredini, a pour vocation de devenir leader sur le marché du tourisme spatial au cours de la prochaine décennie. Ainsi, Michael López-Alegría astronaute professionnel engagé par Axiom Space, Eytan Stibbe, ancien pilote de chasse et homme d'affaires israélien, et Larry Connor et Mark Pathy deux hommes d'affaires nord-américains ont séjourné huit jours à bord de l'ISS. Cet équipage ne se considérait pas comme des touristes en vacances dans l'espace, mais comme des membres de l'équipage de l'ISS en participant à des dizaines d'expériences scientifiques. Cette mission revêt un point fort dans l'histoire du spatial. En effet, elle inaugure une nouvelle phase d'utilisation de l'orbite basse par des entités non gouvernementale et marque ainsi le début du tourisme spatial. Néanmoins, effectuer des expérimentations à bord de l'ISS reste très complexe en raison de la logistique et des défis humains que cela implique.

La Figure 2 résume les missions spatiales qui se sont déroulées de 1998 à 2023.

[3] Conférence de presse du 7 décembre 2021, à Baikanour au Kazakhstan.

Figure 2

Frise chronologique des missions spatiales habitées à bord de Mir, l'ISS et la SSC entre 1998 et nos jours

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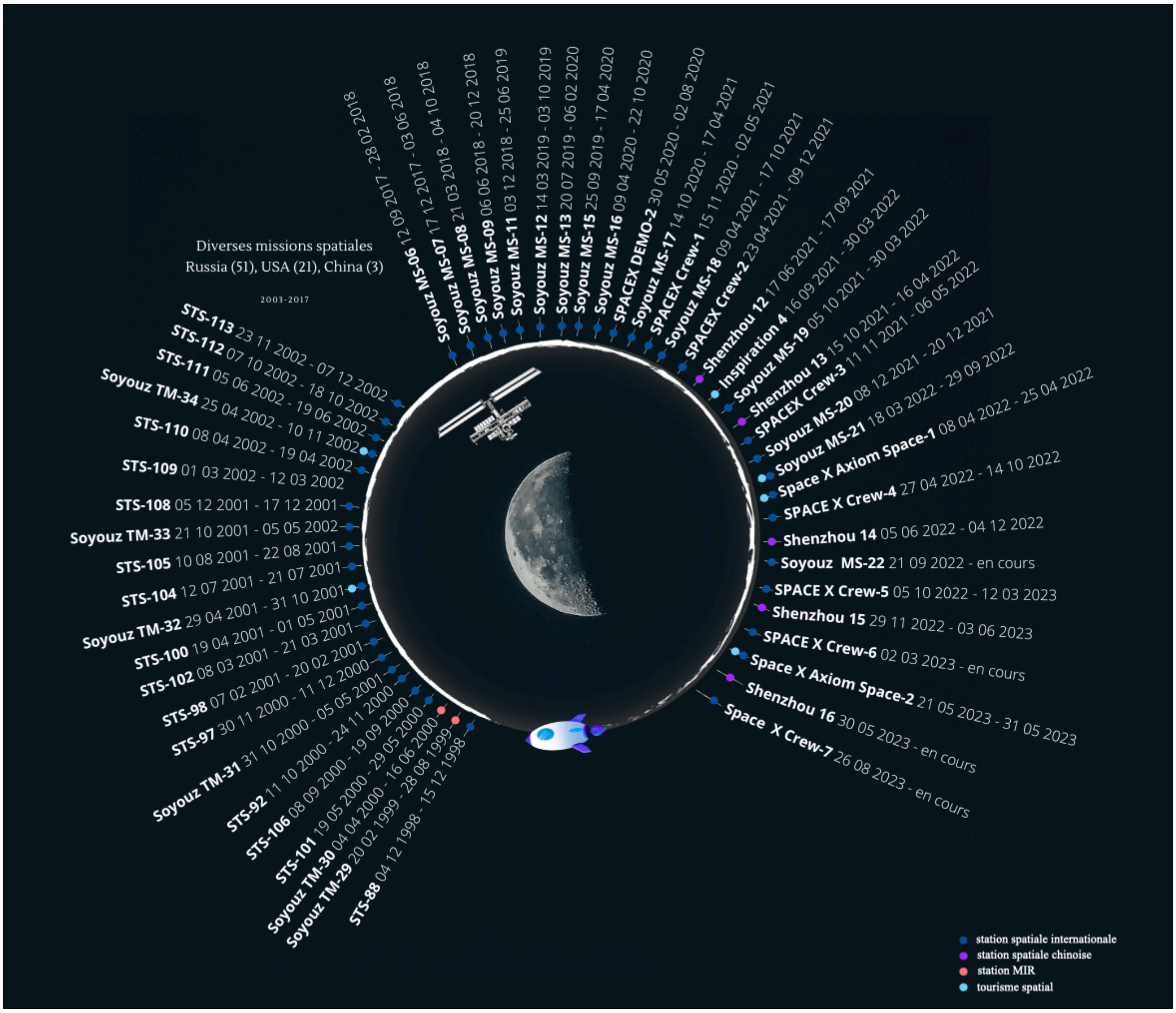


Par beauté, la Terre dispose d'environnements similaires dans les conditions vécues. Ces derniers nommés « analogues » permettent de fournir un portrait plus détaillé de l'impact des environnements extrêmes sur l'être humain.

L'exploration des terrains analogues

Les analogues sont définis comme « un ensemble d'activités entièrement intégrées en appui aux futures missions d'exploration sur la Lune ou sur Mars et/ou simulant ces missions » (Williamson et al., 2007). En effet, ils partagent une ou plusieurs caractéristiques importantes (e.g., l'isolement, le confinement, l'inhabituel et l'extrême). Ils incluent les sous-marins nucléaires lanceur d'engins, les bases de recherche en Antarctique, les missions de survie ou encore les explorations. Ainsi, les études menées dans ces environnements souvent extrêmes sont déterminantes pour l'examen de l'adaptation de l'espèce humaine dans l'espace. Rivolier (1992) définit une situation extrême lorsque les réponses adaptatives dépassent les ressources physiologiques et psychologiques disponibles. En conséquence, les situations extrêmes représentent des conditions inhabituelles confrontant les personnes à leurs limites et les obligeant à mobiliser de manière inédite leurs capacités d'adaptation. Rivolier (1997) fournit quelques éléments de comparaison entre les conditions de vie et de travail dans trois situations analogues : une base polaire de type plateau antarctique, un sous-marin nucléaire, une station spatiale actuelle (Tableau 1).

Tableau 1

Comparaison des analogues aux missions spatiales (Rivolier, 1997)

	Station Polaire	Station Spatiale	Sous-Marin
Isolement	+++	++	+++
Confinement	+	+++	+++
Danger	+	+++	++
Confort de vie	+++	+	+
Promiscuité	+	+++	+++
Importance de l'effectif	+++	+	+++
Gamme d'âges	+++	+	++
Durée du séjour	+++	++	++
Impact hiérarchique de l'extérieur	++	+++	++
Hiérarchie interne	+	++	+++
Problèmes liés à l'hygiène	+	+++	++
Problèmes liés à l'alimentation	+	+++	++
Frustration sexuelle	++	+++	++
Agressivité du milieu extérieur	+	+++	+++
Hétérogénéité nationale	+	+++	NA
Séjour lié à la carrière	+	+++	++
Complexité technique	+	+++	+++
Lourdeur de la tâche	+	++	++
Intérêt personnel dans l'accomplissement de la tâche	+	+++	+

NA = non applicable.

Terra incognita ou Antarctique

L'Antarctique est l'un des lieux les plus hostiles et les plus froids de la planète. Dernier continent à avoir été découvert, les expéditions pour atteindre cette terre infiniment blanche ont demandé un effort incommensurable. Roald Amundsen est considéré comme le premier homme à avoir atteint le Pôle Sud le 14 décembre 1911. Cette époque fut marquée par l'âge héroïque de l'Antarctique dont le point de départ est la déclaration en 1895 du sixième Congrès géographique international : « *That the exploration of the Antarctic Regions is the greatest piece of geographical exploration still to be undertaken ... [and] that this work should be undertaken before the close of the century* » (Keltie & Mill., 1896 ; p. 780).

Depuis, de multiples expéditions polaires se sont succédées. Nombre sont ceux des aventuriers polaires qui ont frôlé voire trouvé la mort. Véritables laboratoires naturels, ces expéditions sont les premières à permettre d'établir les conséquences thymiques et physiques des terrains d'exception (Guly, 2012a). Le récit du Dr Cook reste l'un des plus connus du milieu polaire et des admirateurs des aventuriers. Médecin de la *Belgian Antarctic Expedition* (1898-1899) sous le commandement d'Adrien de Gerlache, il participa à la première expédition qui s'établit sur le continent blanc et passera une année entière enfermée dans son étreinte glacée. Les troubles mentaux et l'ennui étaient plus pesants que la rigueur du climat, malgré un équipement et des vêtements non adaptés au terrain. Son récit (Cook, 1998) met en lumière le risque psychologique de l'environnement sur ces hommes devenus oubliés :

« The curtain of blackness which has fallen over the outer world of icy desolation has descended upon the inner world of our souls. Around the tables, in the laboratory, and in the forecastle, men are sitting about sad and dejected, lost in dreams of melancholy from which, now and then, one arouses with an empty attempt at enthusiasm » (p. 282).

Les carnets personnels des aventuriers polaires rapportent des épisodes de dépression, confusion, paranoïa, idées suicidaires avec pour certains un passage à l'acte. Ce fut le cas lors d'un hivernage à la Station Polonaise Svalbard. En effet, un jeune homme de 21 ans souffrant de sérieux troubles psychologiques (e.g., dépression sévère) dut être évacué (Temp et al., 2020). Pour autant, ce cas reste extrêmement rare. La majorité des hivernages sont sans évacuation possible au cours des mois d'hiver (Grant et al., 2007). Ces troubles psychologiques ont été liés aux caractéristiques de l'environnement qui dégradent rapidement la santé de ces aventuriers mais également à l'absence de sommeil et aux modifications de cycle de veille. Au-delà des journaux des voyageurs polaires, les premières tentatives de discussion des problèmes psychologiques liés à l'exploration polaire sont limitées. Depuis l'avènement de l'International Geophysical Year (1957-1958), puis grâce à la signature du Traité de l'Antarctique (1959) et à la multiplication des stations polaires en Antarctique, les préoccupations d'être le premier quelque part a cédé la place à des questions plus techniques mais aussi plus scientifiques. Cette signature marque l'avènement du début de la recherche en Antarctique et des études s'intéressant à l'adaptation de l'individu. Celles-ci incluent les moyens d'identification des personnes les plus aptes à y travailler. En effet, la ratification du traité par les institutions étatiques a eu pour conséquence de suspendre toutes revendications territoriales et l'autorisation d'établissement de stations dédiées à la recherche. Le continent fut officiellement désarmé, l'extraction de ressources minières voire pétrolières proscrites. C'est une place qui est et doit être entièrement dévouée à la science.

De toute l'ère qui a suivi cette ratification, nombreux étaient les cas d'individus inadaptés aux régions polaires avec un impact psychique conséquent pendant, ou après le retour de l'expédition (Lugg, 2005). Les causes en lien avec l'individu et celles liées à l'environnement restent un enjeu scientifique. Paul Siple écrivait dans l'ouvrage « *Living at the Pole* » (1957) :

« So in a physical sense, we at the Pole were eighteen men in a box. Only with the air of our « bow » could we make our way to the outside world. Nor was there any possibility that we could be rescued should tragedy strike. We would have to remain put until the next summer - in October or November - come what might. There was also the very large problem of how the men going that would be their steady routine for months without respite… Whatever a man was inherently would be intensified during the close-quarters winter night. A mean man grow meaner; a kind man would grow kinder » (p. 1).

Cherry-Garrard, explorateur britannique, considérait une expédition en Antarctique (1910-1913) comme « la pire façon de passer le meilleur moment de sa vie » (Cherry-Garrard, 2003). Son ouvrage « *The Worst Journey of the World* » est toujours considéré comme un grand classique de la littérature sur les expéditions. A lire les plus célèbres ouvrages sur les héros polaires (Cousteau & Dumas, 1953 ; Cherry-Garrard, 2003 ; Shackleton, 2011) ces individus ont vécu bien plus que ce que la plupart en seraient capables. Robert Falcon Scott (1868-1912), véritable héro polaire, et toujours reconnu comme tel de nos jours, finira sa course à la découverte du continent immensément blanc dans une tente, accompagné de deux de ses camarades Henry Robertson Wilson et Edward Adrian Wilson. C'était là aussi l'enjeu de l'ultime traversée de Scott qui expliquera que la communauté scientifique ainsi que la population seront seuls juges des résultats de l'expédition en fonction du succès ou de l'échec de celle-ci. Pour autant, jusqu'au dernier moment il parlera de cette traversée comme tragique tandis que l'ensemble des données scientifiques recueillies a permis des découvertes majeures. A travers ces récits de l’extrême, la motivation de ces hommes, leur courage, leur volonté et leur engagement pour la découverte furent des moteurs essentiels quand ils n’avaient plus de navire, d’eau, ni de nourriture. Lorsque l’environnement des individus n’est plus que chaos (i.e., tempêtes, gerçures, désorientation), l’empathie envers les animaux qui font partie de l’expédition est plus que jamais présente : *« Tous les poney affaiblis, deux d’entre eux ne tiennent pratiquement plus debout. Nous faisons de notre mieux pour les soulager, mais l’Antarctique ne leur vaut rien. Je pense que Scott est plus malheureux pour les poneys qu’ils ne le sont eux-mêmes »* (Cherry-Garrard, 2003 ; p. 405).

Il n’est pas question d’accusation lorsque l’on s’intéresse aux raisons à cause desquelles bon nombre d’hommes sont tombés durant cette épopée dans les glaces mais d’apprendre des leçons que leur engagement et leur courage ont à offrir à l’humanité : celles de la vie confrontée aux extrêmes.

Depuis cette période, de nombreuses avancées technologiques et humaines ont eu lieu permettant à l’espèce humaine de vivre en Antarctique. Les sites des stations de recherche antarctiques se trouvent dans les environnements les plus inhospitaliers habités par l’être humain. Habiter ces terrains le temps d’une mission souligne la volonté et la prouesse technique dont l’humanité est capable pour maintenir en vie de petits groupes d’individus dans un but de partage de connaissances.

La station Durmont d’Urville (*Dumont d’Urville station*, DDU), en référence à l’explorateur qui a découvert la Terre Adélie, est une station polaire située sur la côte de l'Antarctique (66° 39' S, 140° 0' E) ouverte en 1956. L’Institut Paul Émile Victor (*Paul Émile Victor Institute*, IPEV) en assure la gestion fonctionnelle ainsi que la coordination des programmes scientifiques. Elle est le lieu de nombreuses rotations avec l’Astrolabe, navire polaire affrété par l’IPEV, qui assure les rotations des hivernants et du matériel entre l’Antarctique et la Tasmanie. DDU est constituée de plusieurs bâtiments sous la forme d'un campus (Photographie 2). L'hiver se caractérise par une brève période d'aube. On compte 346 heures d'ensoleillement en décembre, contre 9 heures en août. Toutefois, on y observe un rythme solaire quotidien. Les températures oscillent entre -16,7°C en juillet, et -0,9°C en janvier. La moyenne annuelle est donc à -10,8°C, avec des records à -37,5°C et 9,9°C. Située à une altitude de 202 m, le climat y est plus doux que de nombreux autres sites. Sa capacité d'accueil est de 40 personnes en hiver contre 120 en été. Les communications avec le monde extérieur y sont restreintes.

Photographie 2
Station de recherche DDU (66° 39' S, 140° 0' E), Antarctique

A l'inverse, la station polaire Concordia est l'une des trois stations permanentes du haut plateau de l'Antarctique. Les autres sont la station russe Vostok et la station américaine Amundsen-Scott. La station Concordia, aussi appelée « White Mars », a été construite en 2004 et est exploitée conjointement par l'Institut polaire français (IPEV) et le programme national italien de recherche en Antarctique (*national antarctic research program*, PNRA). L'ESA a entamé une coopération avec l'IPEV et le PNRA principalement pour coordonner la recherche en glaciologie, sciences atmosphériques, astronomie et astrophysique, sciences de la terre, technologie et santé. La Direction des sciences de la vie humaine de l'ESA est responsable des programmes de Concordia en médecine, physiologie et psychologie.

Elle est située à une altitude de 3 232 m au Dôme C (75° 06' S, 123° 23' E), à 1 000 km à l'intérieur des terres de la côte de l'océan Antarctique. Le continent du haut Antarctique est l'une des régions les plus froides (température moyenne de -51°C, la plus basse enregistrée étant de -85°C), les plus sèches, les plus inhospitalières et les plus inaccessibles de la planète. L'accès à la station n'est possible que pendant l'été

Antarctique, de mi-novembre à mi-février. En été, la lumière du jour est constante (de mi-novembre à mi-février). En hiver, la nuit est constante pendant une période de deux mois avec un semblant de crépuscule et d'aubes les semaines précédentes et suivantes (mi-mai à mi-août).

Son atmosphère est caractérisée par une hypoxie hypobare chronique, soit une altitude équivalente à près de 4 000 m sur l'équateur, avec une pression atmosphérique d'environ 645 hPa. L'équipage doit y être entièrement autonome, notamment de février à novembre lorsqu'aucun accès à la station Concordia n'est possible, même en cas d'urgence. Les quartiers d'habitation et de travail sont confinés dans de petits bâtiments de deux étages (Photographie 3). L'équipage est multiculturel, avec des langues maternelles, des traditions et des coutumes différentes. Ils ont un accès et une mobilité limitée à l'extérieur des bâtiments de la station, en particulier en hiver, et connaissent donc de longues périodes de sous-stimulation et d'ennui. Les télécommunications sont très restreintes, avec aucun accès en direct à internet et une capacité de courrier électronique périodique très limitée. L'étrangeté de l'environnement est accrue par les très longues nuits et journées polaires, caractérisées par une lumière continue pendant l'été Antarctique et une obscurité dominante en hiver.

Photographie 3
Station de recherche Concordia (75° 06' S, 123° 23' E), Antarctique

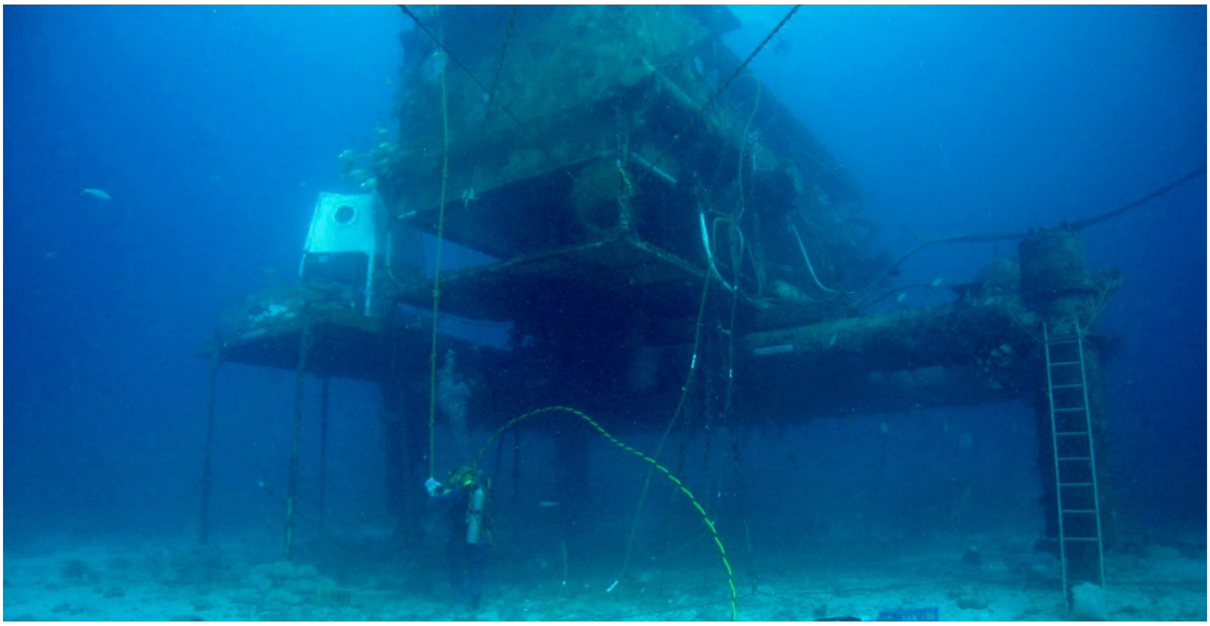
Le silence infini des profondeurs

Les êtres humains peuvent faire l'expérience de l'isolement et du confinement non seulement dans des laboratoires préparés ou des installations de recherche spécialisées sur Terre ou en orbite, mais aussi tous les jours. En effet, les sous-mariniers par engagement professionnel expérimentent des conditions similaires à bord des sous-marins nucléaires lanceurs d'engins (*sub-surface ballistic nuclear-powered missile submarines*, SSBN). La France fait partie des pays ayant encore une présence militaire dans les océans afin de dissuader l'émergence de nouveaux conflits. La classe Le Triomphant (S616) a été inaugurée le 26 mars 1994. Plus grande catégorie de la flotte française, elle fait suite à celle du Redoutable (S611), premier SSBN qui marque en 1963 les progrès technologiques (Photographie 4). La nature de cet environnement éloigné et extrême fait des habitats sous-marins une excellente installation pour la recherche sur les analogues spatiaux. L'éclairage artificiel est programmé pour reproduire un cycle jour/nuit de 24 heures, avec 16 heures d'éclairage diurne (90 à 840 lux) et 8 heures (de minuit à 8 heures) d'éclairage nocturne (principalement rouge et variant de 5 à 220 lux). Durant près de 80 jours, l'équipage est coupé du monde sans aucun moyen de communication (hors code secret). Ils naviguent dans les eaux profondes des océans, se frayant un chemin en n'émettant aucun bruit.

Photographie 4
Sous-marin nucléaire lanceur d'engin français Le Triomphant

Comme pour les stations de recherche en Antarctique, les sous-marins sont de plus en plus étudiés en raison des conditions environnementales similaires aux missions spatiales. La NASA a développé le programme opération de mission en environnement extrême de la NASA (*NASA extreme environment mission operations*, NEEMO) qui consiste en un déploiement sous-marin de 14 jours maximum à bord de la station Aquarius (Photographie 5). Aquarius est un laboratoire océanique sous-marin situé dans le sanctuaire marin national des Keys de Floride. Il est la propriété de l'Administration nationale des océans et de l'atmosphère (*National oceanic and atmospheric administration* en anglais) et est exploité par l'Université de Caroline du Nord Wilmington. Le laboratoire est déployé à trois miles et demi au large, à une profondeur de 60 pieds. Des scientifiques vivent à bord d'Aquarius pendant des missions de 10 jours. Le laboratoire a une profondeur de fond de 62 pieds, une profondeur opérationnelle (sur pilotis) de 47 pieds, une pression intérieure de 2,5 Atos, un espace vital de 43 pieds, des conditions de plongée à saturation (17 heures de décompression nécessaires pour revenir à la surface). Le système Aquarius comporte trois éléments : une bouée de sauvetage à la surface, l'habitat et une plaque de base qui fixe l'habitat au fond de l'océan. A l'intérieur du module principal, se trouvent une pièce de vie avec une cuisine, six couchettes et un espace de travail. La NASA effectue des missions analogues à l'espace à bord d'Aquarius pour une durée maximale de 2 semaines, l'aquanaute effectuant jusqu'à 6 à 9 heures de plongées externes adaptées par jour. La NASA considère le déploiement d'Aquarius comme un analogue terrestre de courte durée pour certains aspects des vols spatiaux. À bord d'Aquarius, le mode de vie en station, le stress de la mission, l'isolement et le décalage du rythme circadien sont reproduits de manière très fidèle. Important pour la fidélité de l'analogie, les équipages NEEMO sont généralement composés d'astronautes qui y séjournent en amont d'une mission spatiale.

Photographie 5
Laboratoire de simulation Aquarius (24° 56' N, -80° 27' O), Floride (USA)



L'exploration de demain

Force est de constater que ces milieux analogues affectent la santé de ceux qui les habitent en mission. Les taux d'apparition de problèmes thymiques voire psychiatriques chez les sous-mariniers et les hivernants seraient similaires aux taux d'apparition d'autres problèmes médicaux tels que cardiovasculaires, génito-urinaires et ORL (Tansey et al., 1979 ; Palinkas et al., 1998 ; Thomas et al., 2000). Certes, il est incontestable que les données recueillies dans ces environnements analogues comportent plusieurs limites telles que les différences entre les terrains, les missions, les caractéristiques des équipages, les responsabilités et niveaux de soutien extérieur (Palinkas, 1990), ou encore la sélection et la préparation des équipages. Toutefois, ces environnements ont tous la particularité d'avoir des conditions environnementales non habituelles (e.g., absence de lumière naturelle, lumière artificielle, concentration élevée de CO2, bruit constant, rythme de quart, promiscuité avec les pairs, températures extrêmes, éloignement des êtres chers) qui challengent l'adaptation des individus qui y séjournent, et donc leur acclimatation.

Or, l'exploration vers le lointain sera au-delà de ce qui est connu, notamment car l'éloignement de la Terre provoquera chez certain un sentiment de solitude hors du commun. La Terre, ce chez soi, cet *ohana* de l'humanité, a été photographiée de la Lune par l'équipage Apollo 8. Devenu célèbre et baptisée *« Earthrise »* ou « Lever de soleil », ce cliché offre la quintessence de l'expérience de l'éloignement (Photographie 1). Pour la première fois, des hommes ont pu observer cette tâche bleu pâle d'un ailleurs tel des extra-terrestres qui n'y seraient jamais allés. Cette prise de vue a fait le tour du monde en nous forçant à repenser notre place fragile et délicate dans un écosystème lui-même fragile et délicat. Carl Sagan (Sagan & Druyan, 2011) ou encore l'astronaute Rusty Schweickart (White, 1987) ont ces mots justes pour parler de cette petite tâche bleu perdue dans les confins noirs :

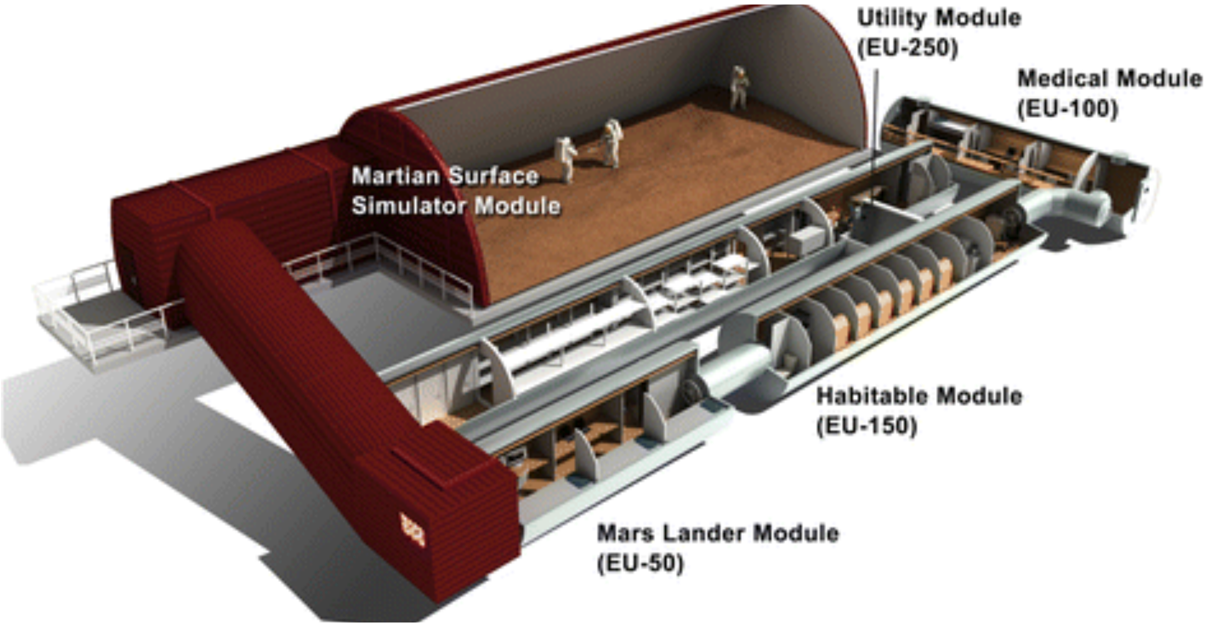
« From this distant vantage point, the Earth might not seem of any particular interest. But for us, it's different. Consider again that dot. That's here. That's home. That's us. On it everyone you love, everyone you know, everyone you ever heard of, every human being who ever was, lived out their lives. . . . There is perhaps no better demonstration of the folly of human conceits than this distant image of our tiny world » (p. 8).

« You identify with Houston and then you identify with Los Angeles and Phoenix and New Orleans . . . and that whole process of what it is you identify with begins to shift when you go around the Earth . . . you look down and see the surface of that globe you've lived on all this time, and you know all those people down there and they are like you, they are you—and somehow you represent them. You are up there as the sensing element, that point out on the end . . . you recognize that you're a piece of this total life » (p. 16).

L'adaptation à ces multiples contraintes pose la réponse de stress comme l'une des questions les plus importantes du facteur humain impliquée dans la réussite de ces voyages futurs. Depuis de nombreuses années, le stress est étudié dans ces terres d'exception, et est une cause fréquente d'effets délétères, qui influencent le bien-être et le succès d'une mission (Sandal et al., 2006). Ces études se font au niveau de l'individu et du petit groupe.

C'est la raison pour laquelle plus récemment certaines missions analogues ont été menées en simulation, comme ce fut le cas lors de la mission Mars-500. Il s'agit du nom du programme expérimental russe, qui s'est déroulé du 3 juin 2010 au 4 novembre 2011 à Moscou et qui avait pour objectif de simuler les conditions rencontrées par un équipage lors d'un aller-retour vers la planète Mars. Ainsi, durant 520 jours, six individus (trois russes, un chinois, un français et un italien) ont pu expérimenter l'isolement et le confinement et explorer si l'être humain était capable de maintenir ses performances malgré ces conditions. L'installation d'isolement Mars-500, anciennement Mars-105 (i.e., 105 jours d'habitation) pour la phase test, était située sur le site de l'Institut des Problèmes Biomédicaux (Institute of Biomedical Problems) à Moscou. L'installation d'isolement comprenait quatre modules d'habitat interconnectés et hermétiquement fermés (modules principaux d'habitation, modules médicaux, modules de stockage et modules de simulation d'atterrissage sur Mars), plus un module externe utilisé pour simuler la « surface martienne » (Photographie 6). Le volume total des modules d'habitat était de 550 m^3. Le module d'habitation principal (3,6 m x 20 m) comprenait une cuisine-salle à manger, un salon, la salle de contrôle principale, des toilettes et six chambres individuelles (2,8 x 3,2 m) équipées d'un lit, d'un bureau avec un ordinateur personnel, d'une chaise et d'étagères pour les effets personnels. Le module médical (3,2 m x 11,9 m) a été conçu pour les examens médicaux et télémédicaux de routine, un laboratoire, des investigations diagnostiques et l'isolement d'un membre d'équipage malade si nécessaire. Le module de stockage (3,9 m x 24 m) abritait une salle de stockage des aliments, une serre expérimentale, une salle de bain (sans eau), un sauna et une salle de sport. L'équipage séjournait dans ces modules dans des conditions d'environnement atmosphérique artificiel à pression barométrique normale.

Photographie 6
Laboratoire de simulation Mars 500, Moscou (Russie)



Encore aujourd'hui, Mars-500 est la seule expérience d'aussi grande envergure qui a été menée pour déterminer l'impact du confinement en vue des prochains longs voyages dans l'espace.

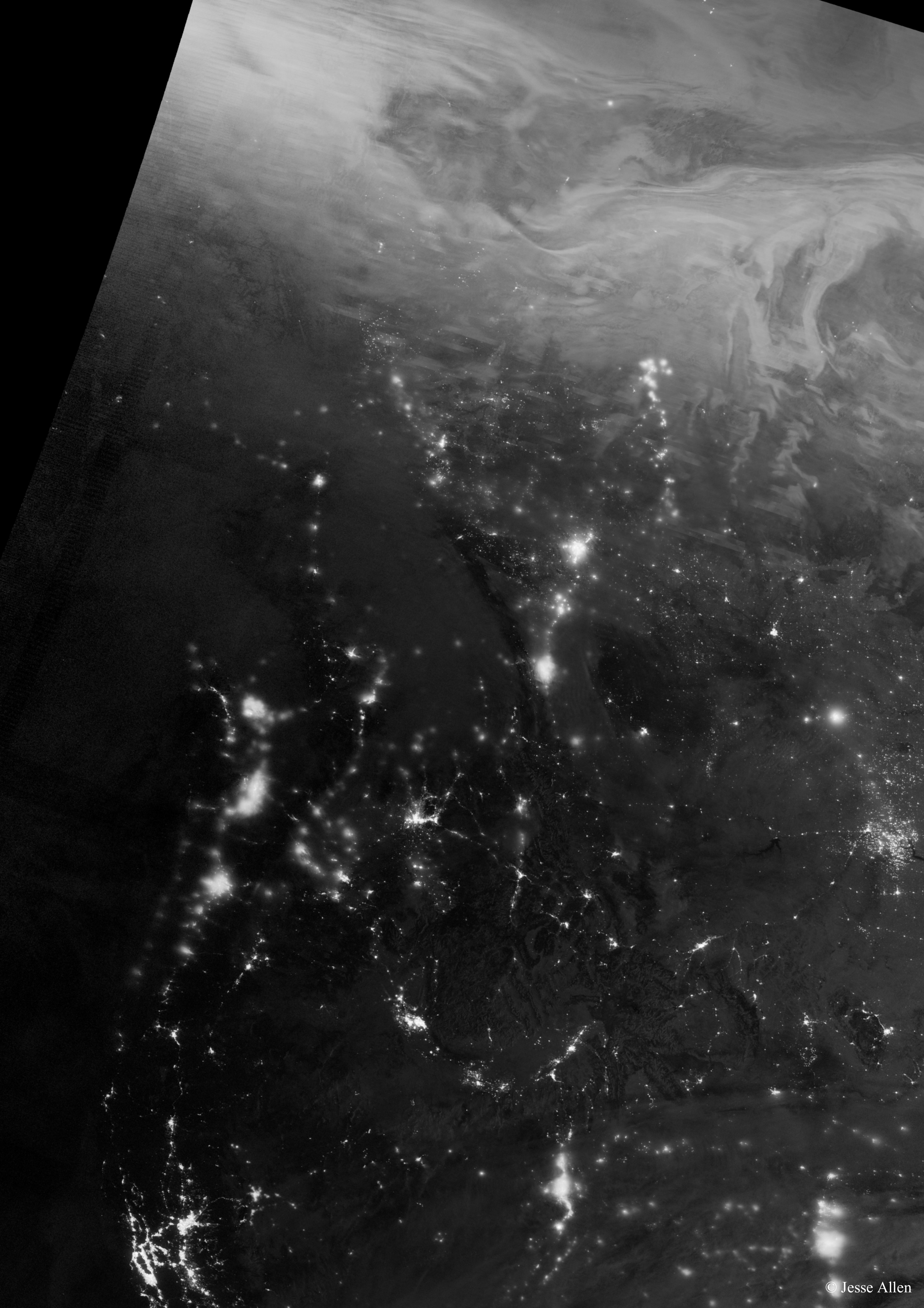
D'autres modules existent dans le monde permettant de réaliser des simulations de la même sorte. L'analogue de l'espace pour la recherche humaine (*human research space analog*, HERA) est un habitat conçu pour servir d'analogue à l'isolement, au confinement et aux conditions d'éloignement dans les scénarios d'exploration (Photographie 7). Situé au Jonhson Space Center, HERA est composé d'un cylindre sur un axe vertical (mezzanine de 69.9m^3 et pièce centrale de 56.0m^3) connecté à un module d'hygiène (14.1m^3) et d'un sas d'entrée (8.6m^3). L'espace total est de 148.1m3. Au premier niveau se trouve la station médicale, la cabine de vol, un atelier de maintenance et la plateforme des opérations. Au deuxième niveau se trouvent une salle de sport, les bureaux et au dernier niveau des couchettes. Depuis son inauguration en 2014, six campagnes se sont succédées allant de 7 à 45 jours.

Photographie 7
Laboratoire de simulation HERA, Floride (USA)

Ces environnements a priori similaires comportent pour autant des différences majeures, que ce soit en termes d'équipage, de caractéristiques environnementales, de durée. Il convient à la communauté scientifique de déterminer leurs apports en vue de la conduite des missions spatiales de demain.

A ce jour, près de 546 personnes ont réalisé des vols dans l'espace depuis l'astronaute Youri Gagarine en 1961 (i.e., 1 heure 48 minutes dans l'espace à bord de la capsule Vostok 1). Depuis peu, l'espace s'est ouvert à de nouveaux individus, appelés « clients de l'espace », tels que Jeff Bezos (20 juillet 2021) et Richard Branson (11 juillet 2021) avant lui. Si ces dernières années la question de l'espace semblait être passée au second plan, depuis un peu plus de deux ans un nouveau vent souffle. Les progrès réalisés dans l'exploration et l'habitation des environnements spatiaux au cours du dernier siècle ont ouvert la voie à des expéditions de plus longue durée (*long duration space flight*, LDSE) au-delà de l'orbite basse terrestre. Imaginez-vous que passer les 400 km par-delà la Terre revêt un terrain inconnu (sauf lors des missions lunaires). En cela, la planète Mars insuffle à l'espèce humaine un nouvel espoir de conquête spatiale. Dès 1953, von Braun publiait « *The Mars Project* » dans lequel il exposait les possibilités d'une expédition sur Mars. Ce projet est le premier connu de colonisation de la planète rouge. Très ancien dans les esprits, ce nouvel esprit de conquête ne date pas d'hier. Les défis technologiques apprivoisés, il n'en restera pas moins la question de « l'élément humain », la composante la plus complexe de la conception de ces futures missions de demain. Notons par exemple que les distances plus grandes par rapport à notre planète Terre et les délais de communications toujours plus importants augmenteront le sentiment d'isolement. Ou encore, les impératifs de santé comportementale (i.e., implications sur les santés psychique, physiologique et/ou sociale) et d'efficacité des performances constituent des défis majeurs pour les missions qui impliquent une augmentation significative du temps passé et de la distance parcourue dans l'espace. Plus que tout, ce voyage représenterait celui d'une vie, un départ sans garantie de retour sain et sauf. Aux confins de l'extrême, l'humanité se retrouvera confronté à des facteurs de stress auquel il pourra difficilement se soustraire. Un état de stress physique et socio-psychologique constant pèsera sur l'équipage, et pourrait même mettre, *per se*, la vie de ses membres en danger. Ceux-ci pourront être la source de problèmes d'adaptation individuel et interpersonnel menaçant la santé et le succès de la mission qui sera confiée à l'équipage. S'échapper ne sera pas une option, rentrer sera inimaginable. Ce fut la réflexion d'un des membres de l'équipage de la station polaire polonaise : *« What I'm gonna do? I can't get to the plane because I'm in the middle of nowhere and even if I could, it's...that...the feeling that you can't go back even if you want, that is really tough »* (Temp et al., 2020 ; p. 146). Un combat pour la vie débutera pour chacun des voyageurs de l'espace dans les confins du vide spatial le portant aux limites de lui-même.

C'est la vocation de cette Thèse qui, en passant de la calotte glacière au plus profond des océans pour se rapprocher de l'immensité du vide spatiale, s'attache à évaluer l'impact des environnements analogues spatiaux, encore appelés environnements « isolés et confinés » (*isolated and confined*, ICE) & « extrêmes et inhabituels » (*extreme and unusual*, EUE), sur les capacités d'adaptation de l'être humain et à expérimenter des contre-mesures ajustées au plus près des besoins. Ce travail ambitionne ainsi de participer, à son niveau, à la connaissance pour un maintien de l'équipage en bonne santé en vue des prochains longs voyages dans l'espace.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INTRODUCTION

Les étoiles n'ont pas l'air plus grandes,
Elles ont l'air plus brillantes

Sally Ride

Si près mais pour autant si éloigné de ses semblables. Ceux qui partent à la quête des étoiles ne reviendront peut-être pas. Un engagement de vie, une promesse d'aller découvrir un ailleurs inexploré. Le prix d'être le premier à frôler une terre de sable rouge, à peupler un monde dans lequel la vie n'a peut-être jamais été. Rien dans l'environnement ne pourra leur rappeler la Terre d'où ils viennent, ajoutant un sentiment difficile à percevoir car inédit en cet instant que son chez soi n'est plus. Quand soudainement, le murmure des bouteilles d'oxygène leur rappelle que devant cette beauté extrême, l'humanité n'a jamais été aussi incertaine. Autant de défis que les équipages au départ des prochaines missions spatiales devront relever. Ces derniers vont challenger leurs capacités à faire face et à s'adapter dans un milieu non plus familier.

Le parcours empreinté par les travaux de cette Thèse suit ainsi celui des caractéristiques des vols spatiaux de longue durée (*long duration space flight*, LDSE). La Figure 3 reprend l'ensemble des articles soumis, en révision ou publiés présenté au sein de ce manuscrit de Thèse.

Figure 3
Overview des articles présentés dans la Thèse
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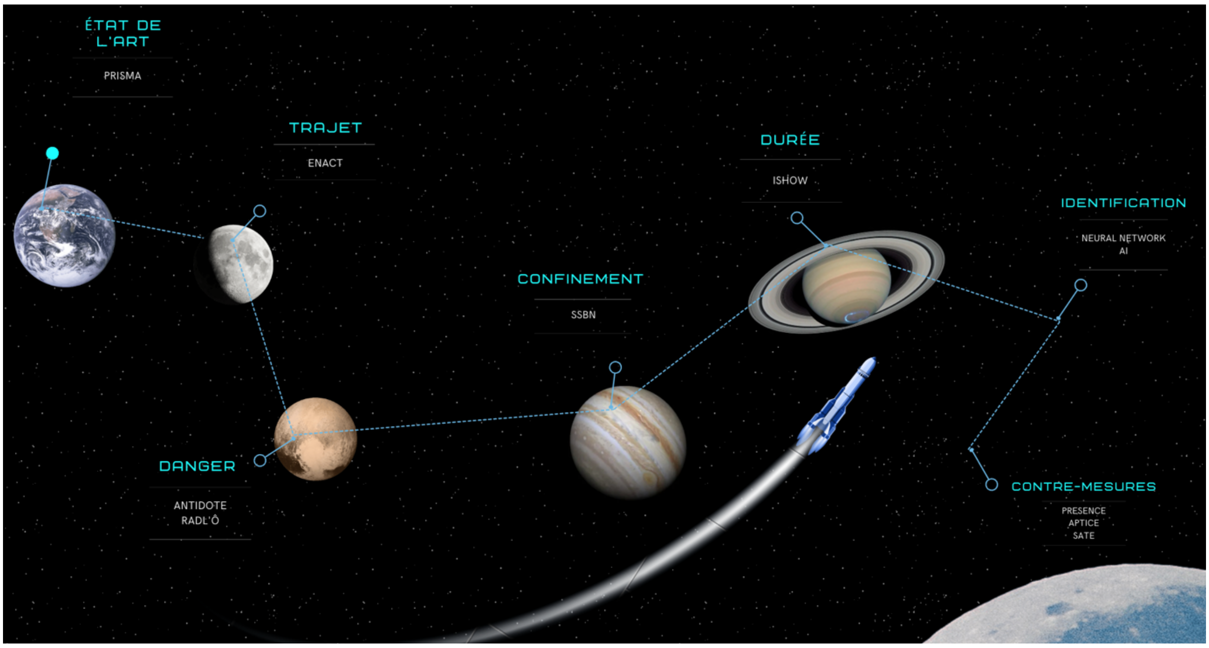


Les acronymes désignés correspondent aux noms des recherches détaillées au sein du manuscrit.

Notre itinéraire a commencé par l'élaboration d'un état de l'art pluridisciplinaire des articles publiés dès 2005 à nos jours afin de recueillir une synthèse la plus récente possible. Cette revue de littérature, intitulée PRISMA, passe en revue selon huit facteurs la question de l'adaptation dans l'espace et ses analogues terrestres. Il s'agit du point de départ de cette mission à savoir établir un état des lieux de l'existant de la littérature. Nous débutons ainsi réellement notre trajet avec la recherche intitulée ENACT qui pose l'étude de l'impact d'un vol parabolique en microgravité sur les réponses psychophysiologiques et sensorielles. Cette dernière pose notamment la question de la préparation de vol à un équipage non professionnel et non sélectionné. Notre mission se poursuivant, de nombreux stresseurs entraveront le trajet de l'équipage. Un enjeu important est d'évaluer dans quelle mesure les réponses psychologiques, cognitives, physiologiques et extéroceptives seront impactées par une situation critique, impliquant de plus la menace invisible d'un environnement. Dans ce contexte, nous avons mené une recherche intitulée ANTIDOTE évaluant les implications physiologiques, psychologiques et olfactive de l'anxiété anticipatrice au cours de simulations au risque nucléaire, radiologique, biologique, et chimique (*chemical, biological, radiological and nuclear*, CBRN) en tenue protectrice de scaphandre. Une deuxième recherche intitulée RAD'LÔ s'est attachée à évaluer les réponses psychologiques, physiologiques, cognitives et sensorielles, incluant l'olfaction, au décours d'une simulation de survie en mer, exercice en situation écologique de haute intensité. Prise ensemble, ces deux situations permettent d'appréhender les capacités adaptatives en situation de stress aigu ainsi que leur préparation. A mesure de l'avancée dans la mission, un des challenges les plus redoutables sur la durée sera celui du confinement. A cet égard, une recherche intitulée ISHOW s'est attachée à explorer les réponses psychophysiologiques et sensorielles durant une année d'hivernage en Antarctique.

Il est à souligner qu'un des points centraux de l'ensemble de ces recherches est notre volonté d'avoir recueilli au maximum des mesures post mission afin d'évaluer la récupération des équipages. Il s'agit d'un élément crucial permettant de mesurer l'impact de la mission sur les capacités adaptatives. Nous verrons que cette question représente un enjeu majeur pour la suite.

La mission mettra à rude épreuve l'adaptation humaine. Une prise en charge sera nécessaire pour améliorer les ressources de l'équipage face aux stresseurs inhérents à la fois à l'environnement et à la mission. En nous appuyant sur certains résultats mis en évidence par les études PRISMA, ENACT, ANTIDOTE, RAD'LÔ, SSBN, et ISHOW, nous avons exploré sur un plan théorique les relations entre intéro- extéroception, trait *mindfulness*, et émotions dans la recherche NEURAL NETWORKS. Nous avons par la suite souhaité caractériser des profils d'adaptation par la recherche intitulée AI pour intelligence artificielle (*artificial intelligence*). En effet, cibler les individus étant les plus à risque et ceux étant à même de maintenir leur adaptation est primordial pour les futurs LDSE. Ce voyage ne peut ainsi se clore sans aborder les contre-mesures individuelles. Ces contremesures ont été ciblées au regard des biomarqueurs d'intégration corps-cerveau mis en évidence dans les études d'adaptation réalisées dans des environnements contraints. Trois approches ont ainsi été explorées dans le cadre de trois recherches intitulées PRESENCE, APTICE et SATE au moyen des dernières avancées médicales et technologiques pour maintenir des conditions opérationnelles optimales et assurer la santé des membres de l'équipage. Ces trois contre-mesures s'inscrivent dans une approche d'*embodied medicine* encore à écrire.

L'ensemble de ces études a reçu une autorisation soit par un comité de protection des personnes dans le cadre des recherches interventionnelles sur la personne humaine (ENACT, ANTIDOTE, RAD'LÔ, SSBN, ISHOW, et SATE) ou par un comité d'éthique (APTICE). Les informations concernant ces autorisations sont précisées dans les articles qui présentent les travaux de recherche réalisés dans le cadre de ce travail.

Annonce de plan

Au décours de ce manuscrit de Thèse, c'est le voyage dans un espace hors du temps qui va être présenté. Plongé dans la peau d'un équipage en mission LDSE et en route vers une contrée incertaine, il n'est pas possible de traverser une zone noire d'étoiles sans en expliquer les concepts théoriques qui seront abordés au sein des différentes recherches. Dans la mesure où il est question des mécanismes d'adaptation sous contrainte et donc face à des stresseurs importants, définir ces questions est important. Avant de s'engager plus avant, nous allons ainsi vous présenter les théories portant sur l'adaptation et le stress en introduction.

Le premier chapitre posera le contexte de la Thèse en retraçant l'état de l'art et en présentant la revue de littérature PRISMA.

Le deuxième répondra au premier objectif expérimental de la Thèse qui porte sur l'impact des environnements analogues à l'espace en environnement isolé et confiné (*isolated and confined environment*, ICE) et en environnement extrême et inhabituel (*extreme and unusual environment*, EUE) sur les professionnels.

Le troisième chapitre répondra au deuxième objectif expérimental de la Thèse à savoir caractériser des profils d'adaptation et proposer des contre-mesures aux sujets les plus à risque de mal-adaptation.

Adaptation et stress : définitions & mécanismes

De la santé aux facteurs de stress et réciproquement

L'organisation mondiale de la santé définit en 1946 la santé comme « un état de complet bien-être physique, mentale et social, et ne consiste pas seulement en une absence de malade ou d'infirmité » (OMS, 1946 ; p. 100). Elle constitue « l'un des droits fondamentaux de tout être humain, quelles que soit sa race, sa religion, ses opinions politiques, sa condition économique ou sociale » (OMS, 1946 ; p. 100). Cette définition fut actualisée en 1984 en y ajoutant un processus dynamique. Il s'agit d'une « mesure dans laquelle un groupe ou un individu peut, d'une part, réaliser ses ambitions et satisfaire ses besoins et, d'autre part, évoluer avec le milieu ou s'adapter à celui-ci ». C'est dans ce cadre conceptuel général que cette thèse s'inscrit (OMS, 1986 ; p. 1). Selon Rivolier (1989, p. 153), un état de bonne santé correspond à « une intégration aboutie des structures organiques, psychologiques et sociales ». Amiel (1986) rappelle que la santé mentale fait partie de la qualité de vie d'un individu. D'après ces définitions de la santé, l'absence de maladie n'est pas suffisante pour pouvoir déterminer la santé d'un individu. La santé est un état inséparable de l'adaptation de l'espèce humaine soulignant l'importance des interactions entre l'être humain et son environnement. Force est de constater que cette interaction est permanente, l'environnement étant changeant instant après instant (Varela, 1993). Ces changements constituent des stresseurs face auxquels la réponse apportée par chacun est plus ou moins efficace pour réagir à la demande de façon ajustée et/ou pour récupérer rapidement (Selye, 1956). Ces constats posent la nécessité de considérer que l'adaptation à l'environnement est en jeu en permanence et que l'efficacité de cette réponse est gage d'un maintien de bonne santé. Cette dynamique d'interaction a été conceptualisée dès les années 1980 par Lazarus et Folkman (1984) en termes de modèle transactionnel du stress. En conséquence, l'individu ne peut demeurer en bonne santé qu'en essayant de minimiser le coût d'interaction avec son environnement en constante évolution. La qualité des interactions qu'il entretient avec le monde qui l'entoure joue ainsi un rôle clé et fondamental dans l'adaptation ; dont dépend l'état de santé.

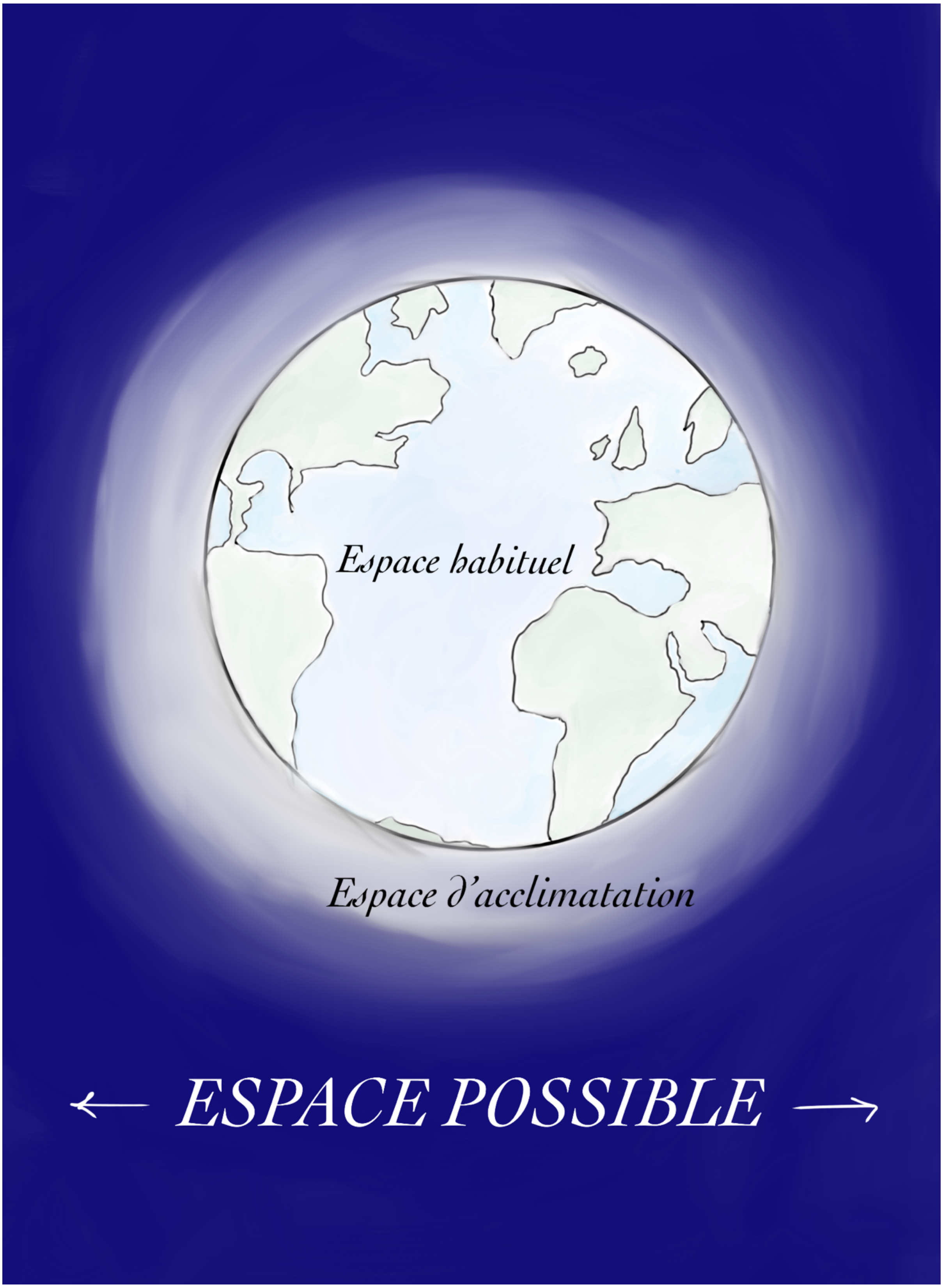
La bonne santé n'est pour autant pas synonyme de bien-être, ce sentiment général d'agrément, d'épanouissement que procure la pleine satisfaction des besoins du corps et/ou de l'esprit. Ainsi, le bien-être revêt des caractéristiques expérientielles et émotionnelles positives (Ryff, 1995 ; Ryan & Deci, 2001 ; Sin & Lyubomirsky, 2009). Récemment, Huppert et So (2012) ont défini le bien-être comme un concept multiple incluant la compétence, la stabilité émotionnelle, l'engagement, le sens, l'optimisme, l'émotion positive, les relations positives, la résilience, l'estime de soi et la vitalité. Également, le bien-être a été défini comme tout ce qui est affectif, comportemental ou cognitif et qui est important dans la vie d'un individu (Rath & Harter, 2010). Ces définitions ne font pas encore l'objet d'un consensus au sein de la communauté scientifique.

La prise en compte du bien-être comme acteur de la bonne santé s'inscrit dans le champ récent de la psychologie positive, champ de la psychologie qui étudie les conditions et processus qui contribuent à l'épanouissement ou au fonctionnement optimal des personnes, groupes ou institutions (Gable et al., 2005). La question de l'étude scientifique du fonctionnement humain optimum s'inscrit comme un enjeu d'adaptation dans des environnements extrêmes qui sur-sollicitent les capacités d'adaptation de l'espèce humaine (Valiunas, 2010).

L'ensemble de ces éléments de définition inscrit la question des conditions de la bonne santé et de son maintien comme un enjeu de faisabilité et de viabilité pour l'installation de bases spatiales pérennes et pose l'enjeu général de ce travail de recherche. Faire vivre des équipages dans l'espace c'est soulever le problème de l'adaptation, c'est-à-dire celui du maintien de l'état d'homéostasie retrouvé dans un nouveau milieu de vie. Certes, il convient de considérer que l'adaptation dans ces environnements spatiaux ne permette pas une habituation aux conditions physiques de l'environnement mais seulement une acclimatation autorisant la vie sans l'inscrire dans un fonctionnement homéostasique et induisant un état de stress qui serait consubstantiel à toute vie spatiale (Figure 4). Toutefois, le terme d'adaptation est largement utilisé pour mentionner la psycho-cognition.

Figure 4

Environnement inhabituel extrême menant à l'adaptation sans mettre en jeu la survie



Les fondements du stress entre définition et régulation

La notion de stress vient du vient du latin *stringere* qui signifie tendre, raide, serré. Considéré comme une force ou une pression, d'une forte influence, agissant sur un objet physique (Rivolier, 1989), le stress est devenu un objet de recherche depuis sa conceptualisation par Hans Selye en termes de syndrome général d'adaptation (*general adaptation syndrome*, GAS) (1946). Pour autant, Cannon dès 1927 avait développé une théorie du stress comme réaction physiologique liée aux changements de l'environnement externe (e.g., changement de température extérieure) ou interne (e.g., émotions, pensées) et visant à rétablir l'état d'équilibre à savoir l'homéostasie. L'homéostasie est l'ensemble des processus dynamiques de l'organisme permettant de maintenir de manière constante son milieu intérieur en dépit des variations du milieu extérieur.

Le stress est défini comme « l'ensemble des réactions non spécifiques de l'organisme à toute demande d'adaptation qui lui est faite » (Selye, 1946 ; p. 119). Il s'agit d'un processus composé de réactions liées à des états physiologiques qui surviennent en réponse à différents stimuli externes appelés stresseurs ou agents stressants. Un stresseur caractérise ainsi toute situation qui active les voies du stress, indépendamment de sa nature, de son intensité et de sa durée. Selye (1956) a décrit le GAS comme une activation de l'axe hypophyse-surrénale ; cette conception est toujours d'actualité en médecine et en sciences (Selye, 1946 ; 1956). Trois phases d'adaptation de l'organisme en réponse à une situation de stress caractérisent le syndrome général d'adaptation (Figure 5) :

1. La première phase est celle de la réaction d'alarme ou aigue qui se caractérise par un ensemble de réactions physiologiques médiées par la voie sympathique du système nerveux autonome (*autonomous nervous system*, ANS) (e.g., augmentation de la concentration sanguine, tachycardie).
2. La deuxième phase est celle de résistance qui permet à l'organisme de durer pour répondre à un stresseur qui se prolonge. Elle s'appuie sur l'axe corticotrope. Cette phase caractérise une sollicitation intense dans la durée de l'organisme.

3. La troisième phase est celle de la récupération. Elle implique notamment la voie parasympathique, encore appelée vagale[4], de l'ANS. Si cette réponse définit l'*eustress*, considéré comme une réponse normale de l'organisme, il convient de souligner que cette troisième phase devenir une phase d'épuisement lorsque le stresseur perdure et que les mécanismes de réponse ne permettent plus de s'adapter et cèdent. On parle de *distress* (Figure 5). Cette phase intervient également lorsque l'agression, devenue trop intense, ne permet pas une récupération suffisante.

Figure 5
Les trois phases du syndrome général de l'adaptation conduisant à l'épuisement selon Selye (1956)
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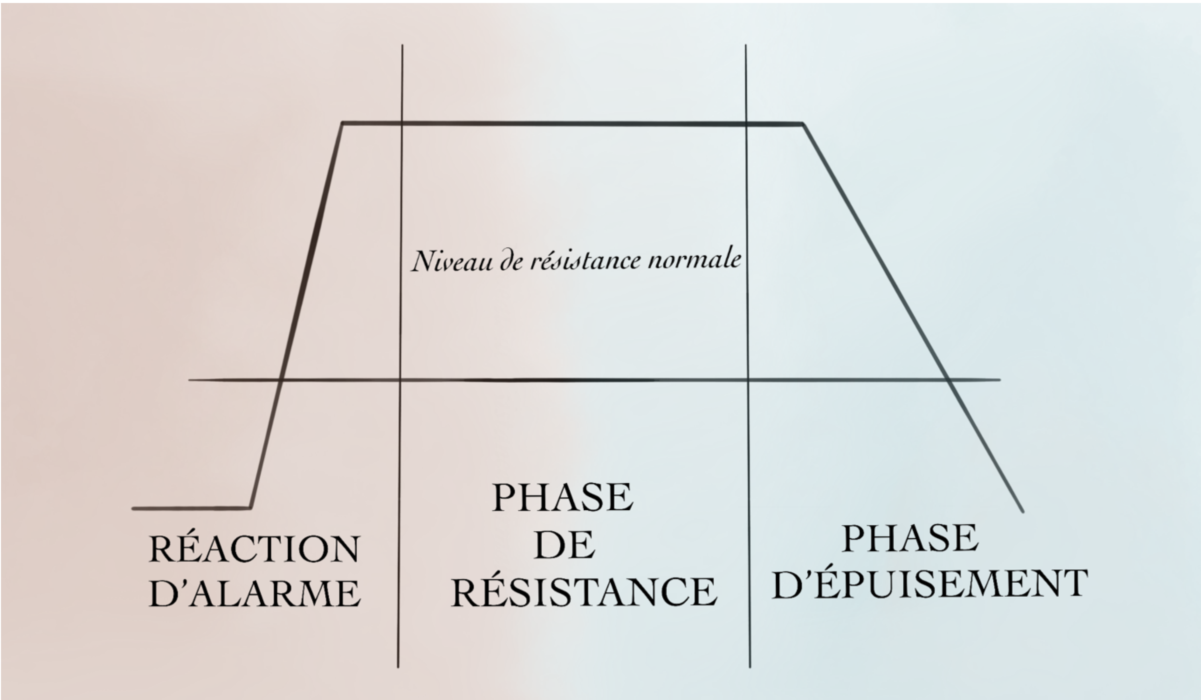

Lorsqu'il est bien régulé, le stress traduit donc un mécanisme physiologique, activé par la contrainte perçue, gérant les coûts biologiques aigus et chroniques (*eustress*). En effet, en fonction du nombre de facteurs la réponse de stress sera variable. Elle dépend du caractère aigu (i.e., courte durée temporelle) ou chronique (i.e., durée temporelle

[4] Dans ce document, les adjectifs parasympathique et vagal seront utilisés l'un et l'autre avec la même acception.

prolongée). La réponse immédiate à un facteur de stress aigu implique des ajustements rapides à la fois de la physiologie et de la cognition afin de préparer l'organisme à faire face à une situation menaçante. L'élément central de celle-ci est la libération des hormones adrénaline et noradrénaline dans la circulation sanguine. La réaction en chaine déclenche une augmentation de la préparation artérielle, du pouls et de la respiration. Ainsi, le cœur bat plus vite et est plus demandeur en sang, les vaisseaux sanguins quant à eux se dilatent afin de fournir un apport plus conséquent en oxygène aux muscles, de même que les bronches pour augmenter la capacité respiratoire, les pupilles se dilatent permettant un afflux lumineux plus important, les temps de réactions sont accélérés, les muscles squelettiques sont activés. Les glandes sudoripares stimulées, le sang est transféré des extrémités du corps vers le cœur, le cerveau et les muscles.

Le socle commun qui mène au risque d'un *distress* est l'incapacité de l'individu à adapter sa réponse de stress en durée et/ou intensité au décours des phases du GAS. Une augmentation du stress a été associée à des troubles de santé mentale et physique, notamment les troubles anxieux, la dépression et les maladies cardiovasculaires (Martin, 1997 ; Dickerson & Kemeny, 2004 ; Wetherell et al., 2006). Enfin, il s'avère nécessaire de préciser que la qualité de la récupération après chacun des stresseurs conditionne la réponse de stress lors de la sollicitation future. Nous parlerons d'allostasie pour décrire la stabilité de l'organisme à travers le changement via des mécanismes régulateurs qui assurent l'indépendance du milieu intérieur face au milieu extérieur. En conséquence, l'allostasie implique des mécanismes d'auto-régulation afin d'assurer la régulation du milieu intérieur en prévision ou suite à un coût environnemental. Lorsque celle-ci s'avère insuffisante, le retour à un équilibre homéostatique n'est pas possible. Cette charge allostatique ou *allostatic loads* intervient lors d'une accumulation de conséquences négatives due à un stress chronique, et renvoie à la notion d'usure. Lorsque la demande environnementale dépasse les ressources qu'un individu peut mobiliser, il en résulte une surcharge allostatique ou *allostatic overlead*. Entre en jeu la dérive vers le risque de pathologies chroniques en raison du coup biologique de fonctionnement en dehors de sa zone d'homéostasie. En cas de sollicitation trop intense, un stresseur peut anormalement être mémorisé. Cette genèse constitue les prémisses de l'évolution vers un état de stress post-traumatique.

La qualité de la régulation de l'homéostasie résulte de la coordination dynamique de nombreux acteurs neurobiologiques. Parmi ces boucles de régulation, la régulation autonome est un acteur clé de la régulation homéostasique. L'ANS ou système nerveux viscéral est la partie du système nerveux responsable de la régulation de certaines fonctions automatiques de l'organisme (e.g., rythme cardiaque). Il se trouve dans une des parties du système nerveux central (*central nervous system*, CNS ; i.e., encéphale et moelle épinière). Plus spécifiquement, il permet de mesurer le danger et de répondre de manière appropriée à ce dernier. Il comprend deux sous-systèmes antagonistes à savoir le système nerveux sympathique (*sympathetic nervous system*, SNS) et le système nerveux parasympathique (*parasympathetic nervous system*, PNS) (Figure 6).

Figure 6

Effets du système nerveux autonome sur l'organisme

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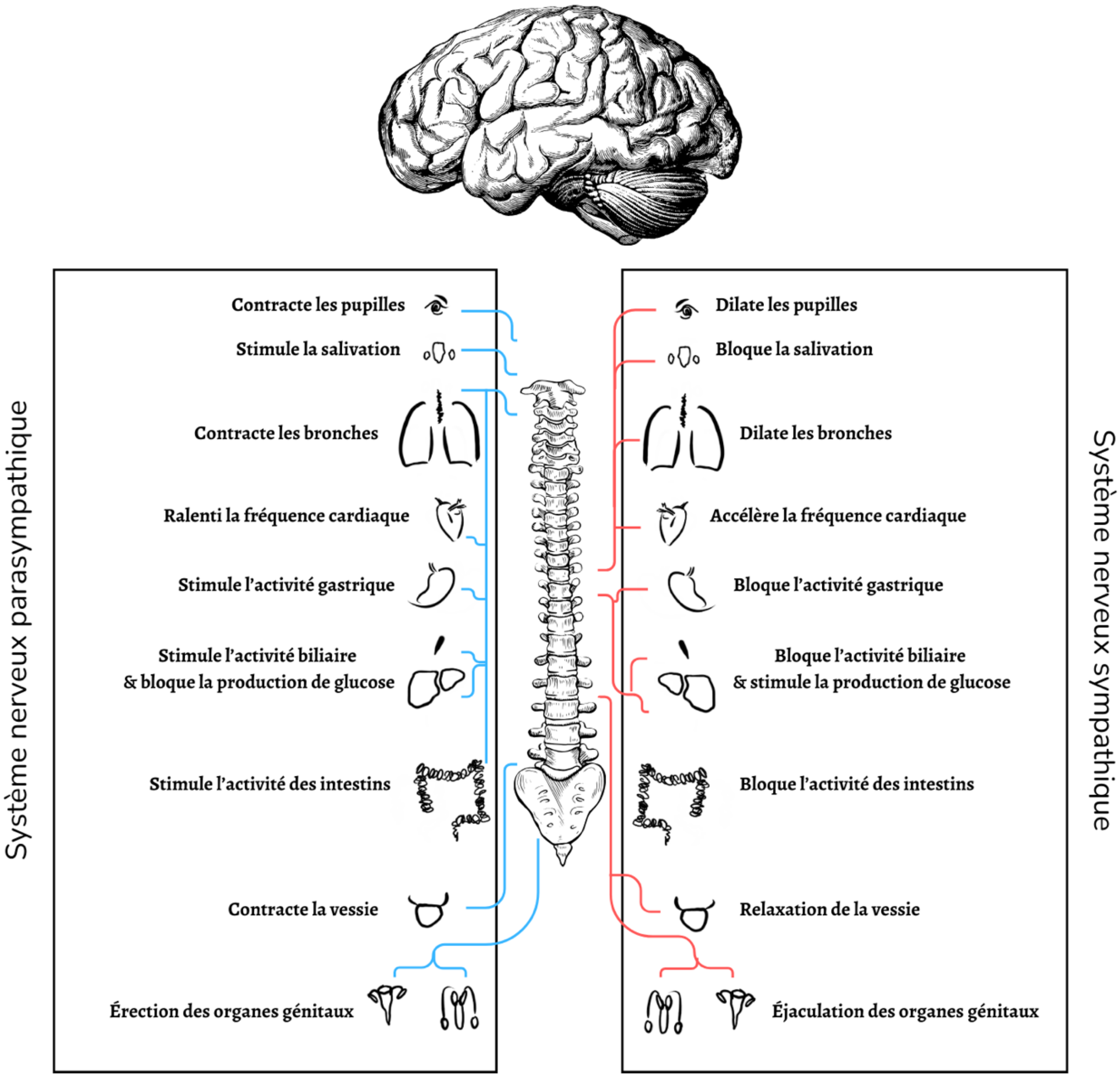

Le SNS est *ergotrope* (i.e., producteur d'énergie) et ainsi en charge de la réaction comportementale *du flight ou fight* (i.e., fuir ou combattre). Le PNS est *trophotrope* (i.e., animateur de fonctions métaboliques restauratrices d'énergie) et jouerait le rôle de régulation locale permettant de revenir à un état d'équilibre. Ces derniers ont une organisation neurophysiologique propre à chacun mais fonctionnent en interaction permanente, à la fois opposés et complémentaires. En situation de stress, la détection rapide d'une menace provoque une activation automatique de l'amygdale entrainant par répercussion une activation du noyau noradrénergique du tronc cérébral, le locus cœruleus. L'activation du locus cœruleus permet la libération d'adrénaline par les glandes médullosurrénales et l'activation du système sympathique. Les efférences sympathiques activatrices assurent alors l'autorégulation de l'organisme via son action sur la motricité des viscères et la libération d'hormones (i.e., acétylcholine, catécholamines). Les efférences parasympathiques agissent comme un antagoniste à ces réactions et entrainent une diminution du rythme cardiaque ainsi qu'un relâchement des muscles lisses involontaires, permettant au corps de régénérer l'énergie utilisée après une activation de la branche sympathique. L'ANS se décompose en deux voies : une voie vestigiale, dorsale, responsable de la réaction de défense, et une voie centrale mise en jeu dans la régulation anabolique (Figure 7). L'action de l'ANS sympathique est médiatisée par la production de noradrénaline au niveau de ses synapses et par la libération des hormones médullo-surrénales, adrénaline et noradrénaline ; celle de l'ANS parasympathique par la libération d'acétylcholine. La récupération passe par des voies anaboliques qui engagent l'activation du tonus parasympathique.

Figure 7
Le système nerveux parasympathique et ses afférences activatrices/antagonistes
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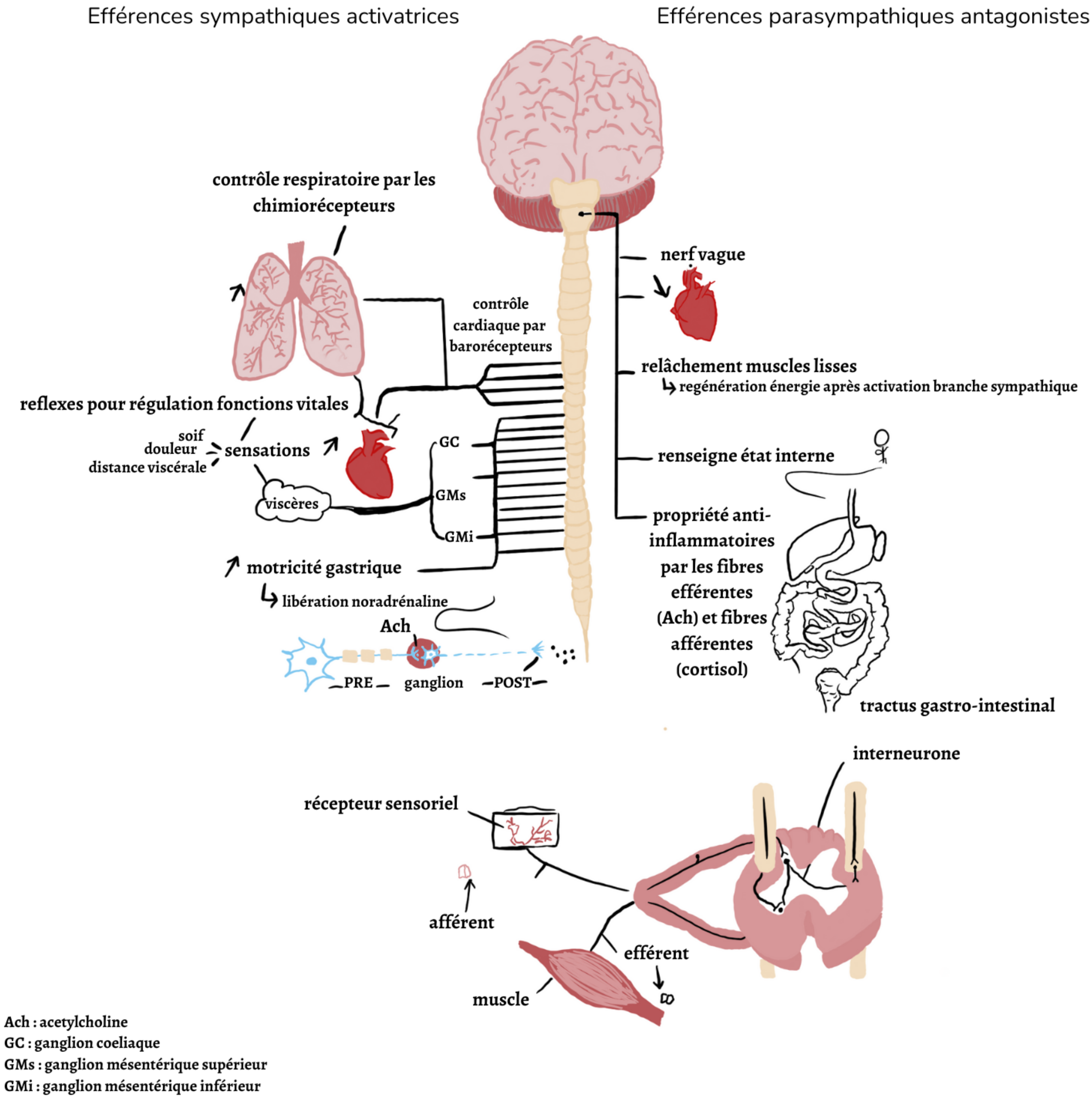

Aussi le stress doit être considéré comme une fonction normale quand le retour à l'homéostasie est possible (*eustress*) qui est mise à mal quand le retour à l'homéostasie n'est pas possible. Le coût allostatique trop élevé traduit l'émergence d'une hystérésis (i.e., propriété d'un système dont l'évolution sera différente en fonction d'une action physique) conduisant au *distress* et à ses risques pour la santé que le *distress* soit permissif ou causal dans les pathologies développées. Cette réaction de stress est coordonnée par le CNS pour permettre le couplage adéquat de l'individu à son environnement. L'ensemble des acteurs du stress agissent en interaction permanente pour permettre une adaptation, instant après instant.

L'approche neurobiologique du stress

La découverte des réseaux de stress chez l'espèce humaine est récente. Les zones neuroanatomiques participant à la réponse de stress comprennent l'hypophyse, l'hypothalamus, le système limbique (i.e. bulbe olfactif, pédoncule olfactif, bandelette olfactive, aire olfactive corticale, amygdale, hippocampe, fornix, gyrus dentarus, subiculum, septum lucidum, aire septale, noyaux de septum, cortex pyriforme), la formation réticulée, et le néocortex (Figure 8). L'information issue des récepteurs sensoriels (i.e., vision, audition, goût, odorat, olfaction, proprioception, viscéroception) capture le milieu environnement et remonte vers les régions susmentionnées. L'information viscéroceptive ou intéroceptive est véhiculée par le système vagal.

Figure 8
Vue supérieure médiale droite après coupe sagittale partielle d'un cerveau humain
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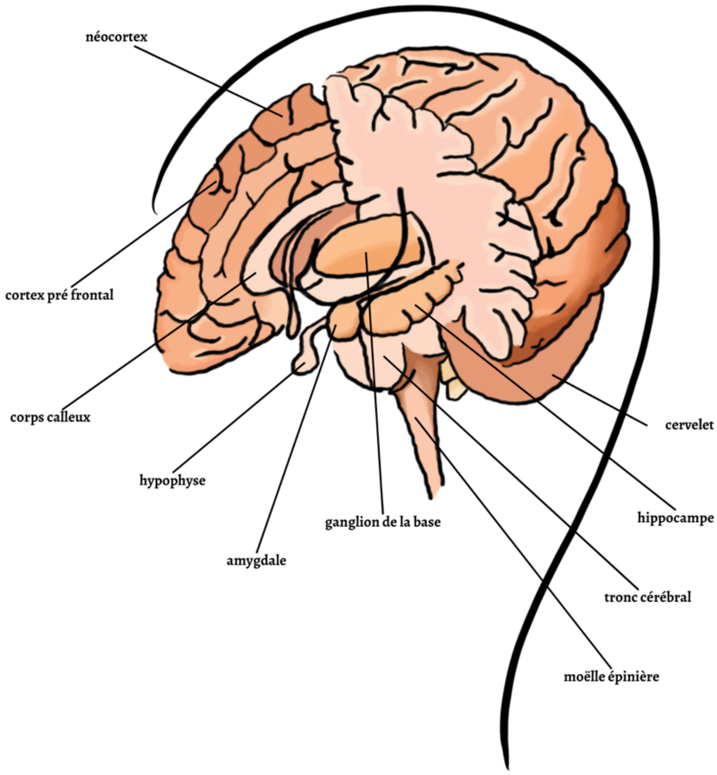


Le raisonnement évolutif soutient le rôle du cortex préfrontal (*prefrontal cortex*, PFC) dans la régulation de l'activité sympathique par défaut (Brosschot et al., 2017). Plus spécifiquement, la réponse au stress est médiée par les zones sous-corticales du cerveau par le cortex préfrontal ventromédian (*ventromedial prefrontal cortex*, vmPFC). Il en est une composante essentielle du réseau de contrôle des facteurs de stress aigus et chroniques. Ajouté au complexe amygdaloïde et aux neurones sérotoninergiques du noyau du raphé dorsal (*dorsal raphe nucleus*, DRN), ces structures interconnectées établissent un réseau neuronal déterminant la vulnérabilité ou la résilience d'un individu au stress chronique. Le DRN est également connecté aux neurones GABAergiques et glutamatergiques du vmPFC. L'augmentation de l'activité des neurones du DRN diminue l'activité du PFC médian et réduit leur activité sur l'amygdale. Lorsque la sécurité est mise en doute, l'inhibition sous-corticale par le vmPFC est diminuée et l'activité de l'amygdale favorisant les mécanismes physiologiques et comportementaux par défaut via une action du SNS pour faire face à la menace (Brosschot et al., 2016). A l'inverse, quand une situation est perçue comme sécure, l'activité de l'amygdale est à nouveau inhibée par le PFC (Brosschot et al., 2016). Intervient alors un système de frein sous-tendu par le PNS (Kim et al., 2018a ; Brosschot et al., 2017 ; Brosschot et al., 2018). Cette conception fait référence à la théorie polyvagale développée par Porges (2001) qui détermine comment un organisme est capable de s'adapter aux variations de l'environnement. Selon cette théorie, notre cerveau évaluerait continuellement les risques présents dans l'environnement, et ce de manière majoritairement inconsciente. Elle se concentre donc sur la communication entre le cœur et le cerveau. Cette dernière s'effectuerait par le nerf vague (*vagus nerve*, VN) qui assure l'innervation parasympathique du cœur, redonnant alors place au rôle du PNS et au rythme cardiaque comme fenêtre pour étudier le fonctionnement du PNS. Porges souligne la dimension « neuroperceptive » de l'ANS. La neuroception, plus classiquement utilisée que le terme de neurperception, se réfère à la perception inconsciente par l'ANS des signaux de danger et de sécurité de l'environnement dans lequel un individu évolue instant après instant. La particularité de l'ANS est qu'il contient à la fois des fibres afférentes et efférentes impliquées dans des boucles de rétroaction entre le CNS et les organes mobilisés dans l'action. La perception inconsciente de l'environnement interne par les afférences vagales va modifier l'état attentionnel et l'activité de l'ANS qui en découle. La neuroperception va déterminer laquelle de ces branches va être activée pour faire face à la situation. Au sein de cette genèse, intervient également le modèle d'intégration neuro-viscérale développé par Thayer et ses collaborateurs (Thayer & Lane, 2000 ; Thayer & Siegle, 2002 ; Thayer & Lane, 2009). Ce modèle décrit les interconnexions entre le PFC et l'activité cardiaque. Il postule que l'activité parasympathique servirait d'indicateur de l'efficacité de ces interconnexions (Thayer & Lane, 2009). Ainsi, plus l'activité parasympathique au repos est élevée, plus l'individu serait capable de s'adapter aux stimuli environnementaux.

L'approche psychologique du stress

Dans le domaine psychologique, les capteurs déterminent une représentation du monde qui est la manière dont le cerveau s'ajuste à un flux d'information constant. Le cerveau s'énactant au cours de l'interaction avec le monde s'ajuste sur un mode de fonctionnement prédictif probabiliste. L'idée que l'on a du monde sert de base à l'action qui est lancée et cette dernière est régulée selon les résultats attendus ou non qu'elle entraine. Encore aujourd'hui, les processus psychologiques de réponse au stress peinent à s'articuler avec l'approche neurobiologique du stress.

Pour autant, l'étude du stress en psychologie s'appuie sur de nombreux cadres théoriques, apportant chacun des éléments de compréhension et/ou d'aide à la prise en charge du stress. Les approches basées sur les stresseurs s'attachent à caractériser les caractéristiques des changements de l'environnement. Les vols spatiaux et les environnements analogues ont été caractérisés par Herman et Cullinan (1997) comme étant le terrain de facteurs de stress systémiques (i.e., qualités physiques tels que l'hypoxie, le bruit ambiant et une faible activité physique) ou processifs (i.e., caractéristiques psychologiques tels que le manque d'intimité, l'ennui, la fatigue et les problèmes interpersonnels). Toute situation qui active les voies du stress est un stresseur indépendamment de sa nature, de son intensité et de sa durée. Celui-ci peut être extérieur au sujet, ou généré par son propre organisme, la psychologie distingue les stresseurs externes des stresseurs internes. Les stresseurs externes sont imposés au sujet par un changement de l'environnement. Il s'agit des stresseurs les plus étudiés. Les stresseurs internes (e.g., affects, pensées) font quant à eux l'objet d'une moindre attention. Ils posent la question de la représentation mentale que l'individu a de son environnement interne et externe. La notion de représentation implique de considérer comment le monde se matérialise au quotidien dans le cerveau et plus largement dans le corps et des mécanismes de neuroplasticité qui rendent compte de la modification à chaque instant de l'expérience par le cerveau. Indépendamment de leur nature cognitive, physique, émotionnelle, cinq catégories de stresseurs peuvent être décrits d'un point de vue temporel : (i) les stresseurs aigus limités dans le temps (5 à 100 minutes ; e.g., les stresseurs de laboratoire) ; (ii) les stresseurs naturels brefs (e.g., passer un concours ou un examen) ; (iii) les séquences d'évènements stressants (e.g., deuil, catastrophe naturelle) ; (iv) les stresseurs chroniques : évènements caractérisés par leur stabilité sans aucune information sur leur durée (e.g., maladie chronique) ; et (v) les stresseurs distants se caractérisant par des traumatismes (re)surgissant tardivement (e.g., viol, prisonnier de guerre, victime d'attentat) et pouvant dévier vers l'établissement d'un état de stress post-traumatique.

Lupien (2019) a mis en évidence certaines caractéristiques pour rendre compte des changements de l'environnement à risque de générer un *distress*. Ces dernières considèrent chacun des évènements de ce changement sous l'acronyme CINE qui détermine : (1) la perception d'une diminution ou d'une absence de contrôle (e.g., manque de contrôle sur la situation), (2) un évènement inattendu ou imprévisible (e.g., difficulté à anticiper les évènements), (3) la nouveauté d'un évènement (e.g., affronter une situation inconnue), et (4) l'égo menacé (e.g., mise à l'épreuve de ses compétences ou égo dans un contexte social). Ainsi, les stresseurs sont des changements de l'environnement de diverses natures. Il n'existe pas de classification consensuelle mais un *effet dose* (e.g., intensité, durée, répétition) et un *effet vécu* du sujet (e.g., expériences de vie, ressources disponibles).

Ces approches taxonomiques des stresseurs ont été complétées par des approches visant à comprendre les différents processus de réponse pour mieux caractériser leurs impacts sur le fonctionnement psychique (Rahe & Arthur, 1978 ; Vingerhoets & Marcelissen, 1988 ; Miller, 1989). En complément de l'approche cognitive du stress de Lazarus et Folkman (1984) pour expliciter les évaluations et les processus d'adaptation mis en jeu dans la transaction entre l'individu et son environnement en fonction de la situation, des modèles de régulation émotionnelles ont été proposés.

Les modèles de régulation émotionnelles

La régulation émotionnelle se définit comme « l'ensemble des processus automatiques et contrôlés impliqués dans l'initiation, le maintien et la modification de l'occurrence, de l'intensité et de la durée des états de sentiments » (Gross & Thompson, 2007). Plus précisément, la régulation émotionnelle est un processus dont le but est d'influencer les émotions ressenties par un individu, ainsi que la manière dont il les ressent et les exprime (Gross & Feldman Barrett, 2011 ; Gross, 2013). L'étude de ces processus s'attache à comprendre la réponse émotionnelle en termes de valence, fréquence, intensité et/ou durée. Les individus façonneraient leurs émotions et la façon dont ils les vivent et les expriment en exerçant un contrôle via un large éventail de stratégies (Gross, 1998 ; Gross, 2014). La régulation consciente des émotions fait référence à la régulation des émotions liée aux processus cognitifs par lesquels les individus travaillent avec leurs émotions afin de garder le contrôle et/ou de ne pas être submergés (Contardi et al., 2016). Ces régulations émotionnelles visent à modifier chaque expérience et réponse émotionnelle en contexte (Gross & Thompson, 2007 ; Gross, 2015). Selon Gross et John (2003), une bonne régulation émotionnelle est associée à un état de bien-être général et à une meilleure santé psychologique, tandis que 40% à 75% des psychopathologies furent associées à des déficits de régulation émotionnelle (Aldao et al., 2010 ; Gross & Jazaieri, 2014 ; Joormann & Santon, 2016).

Selon Gross et Thompson (2007), la régulation émotionnelle intervient à différents stades de l'apparition de l'émotion. Dans un processus *top-down*, ils proposent de distinguer deux groupes de mécanismes cognitifs de modulation des émotions. D'une part, les mécanismes centrés sur les antécédents de la réponse émotionnelle (i.e., avant que la réponse émotionnelle ne soit produite) et d'autre part, les mécanismes centrés sur la réponse émotionnelle elle-même. Les premiers mécanismes, centrés sur les antécédents de la réponse émotionnelle, comprennent différents processus cognitifs (e.g., sélection de la situation, modification de la situation, déploiement de l'attention, réévaluation). Certains sont considérés comme fonctionnels, tels que l'acceptation, la planification et la réévaluation positive, tandis que d'autres sont considérés comme moins adaptatifs, tels que la rumination, la suppression, l'auto-culpabilisation et le catastrophisme. Les seconds mécanismes, centrés sur la réponse émotionnelle, comprennent les processus de modulation de la réponse émotionnelle selon deux axes orthogonaux. Le premier axe correspond à la valence de l'émotion (agréable/désagréable) et le second concerne la régulation de l'intensité émotionnelle (augmentation/diminution). De cette représentation découlent quatre formes de régulation émotionnelle telles que l'augmentation des émotions désagréables, l'augmentation des émotions agréables, l'atténuation des émotions désagréables, l'atténuation des émotions agréables. Par conséquent, un individu en situation de stress va mettre en œuvre un ensemble de stratégies (conscientes et/ou inconscientes) destinées à réduire l'impact émotionnel de l'événement et/ou à résoudre le problème. En complément, certains auteurs pointent les enjeux de la flexibilité de l'utilisation des stratégies disponibles comme un critère de qualité de réponse émotionnelle et donc de l'adaptation aux caractéristiques de la situation (Carver et al., 1989 ; Roussi et al., 2007).

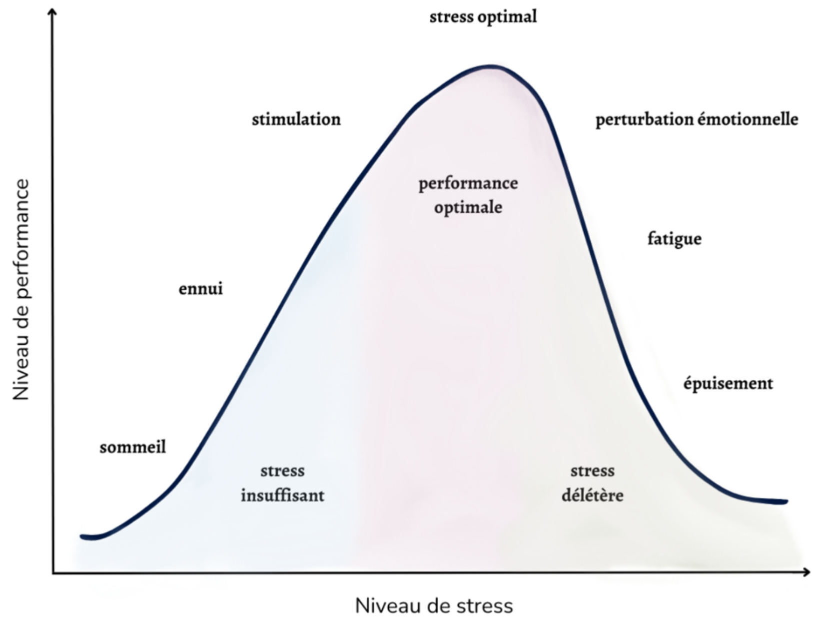
Les structures cérébrales impliquées dans la réponse de stress sont directement impliquées dans le circuit impliquant la régulation émotionnelle. Ils forment un réseau commun impliquant le système limbique qui s'articule en amont avec les zones de détection sensorielle (cortex primaire, thalamus) et corporelle (insula), et en aval avec le cortex préfrontal (ventrolatéral et dorsolatéral, orbitofrontal) et cingulaire (Gross & Feldman Barrett, 2011). Ces éléments de neuroanatomie fonctionnelle offrent des cadres psychophysiologiques de la réponse émotionnelle.

Il a ainsi été proposé que des processus de régulation physiologiques ou *bottom-up* et cognitifs ou *top-down* interviennent dans la régulation émotionnelle et que le processus *top-down* modulerait le *bottom-up* (Park & Thayer, 2014). Des modèles psychophysiologiques ont été décrits pour rendre compte de ces relations *top-down* et *bottom-up*, proposant ainsi une articulation entre les réponses physiologiques et psychologiques. Des augmentations ou des diminutions de la fréquence cardiaque accompagnent également diverses expériences émotionnelles (Servant et al., 2008). Plus largement, les réponses physiologiques émotionnelles sont causées par des changements d'activité dans les composantes sympathique, parasympathique et entérique du système moteur viscéral. Les signes les plus évidents de l'activation physiologique émotionnelle impliquent des changements dans l'activité du système moteur viscéral (Kassam & Mendes, 2013). Ces systèmes physiologiques jouent un rôle majeur en informant le cerveau de l'état de l'équilibre sympathovagal et contribuent ainsi à l'orientation de la réponse émotionnelle, et *in fine* au maintien de l'homéostasie adaptative. Ainsi, la régulation émotionnelle basée sur des changements physiologiques contribue à l'émergence de l'état mental d'un individu en réponse au contexte et à l'environnement dans lequel il évolue. Des études ont souligné une régulation ascendante dans laquelle la conscience intéroceptive est en jeu (Dunn et al., 2010 ; Weng et al., 2021 ; Bernston & Khalsa, 2021). De même, le stress modifie la représentation centrale des processus corporels (Craig, 2002). L'intéroception, caractérisée par la perception des informations corporelles internes, pourrait « médier » la réponse de stress et ainsi jouer le rôle d'intermédiaire (Schulz & Vögele, 2015 ; Bernston & Khalsa, 2021). Elle englobe à la fois les signaux corporels non conscients par le biais d'un encodage et d'une représentation au sein même du système nerveux ainsi que la perception consciente de ces signaux dans le même temps par un individu (e.g., battements du cœur). Les boucles de régulation impliquées dans les voies intéroceptives participent à l'état d'équilibre (Pinna & Edward, 2020). La littérature a mis en évidence que les signaux intéroceptifs et extéroceptifs peuvent être altérés dans un environnement stressant ayant pour conséquence d'impacter l'axe corps-cerveau. Le stress module et ainsi façonne les processus de régulation intéroceptifs au moins à deux niveaux : (1) via une stimulation des axes physiologiques du stress (i.e., implication des récepteurs β1-adrénergique, activation de l'ANS et du système hypothalamo-hypophyso-cortico-surrénalie) et (2) via une diminution du niveau de ressources attentionnelles. En conséquence, un dérèglement des boucles de rétroaction régulatrices de l'axe corps-cerveau, axe bidirectionnel, représente un facteur important dans la genèse de troubles liés au stress. La littérature met en exergue son implication dans le cadre de l'homéostasie et l'allostasie mais également, dans des processus cognitifs et émotionnels complexes (e.g., mémoire, prise de décision, traitement des émotions, interactions sociales, conscience, appropriation du corps, soi) (Dunn et al., 2010 ; Shah et al., 2017 ; Berntson et al., 2019 ; Critchley & Garfinkel, 2017). En effet, le comportement issu de l'adaptation ainsi que la prise de décision optimale sont soutenus voire guidés par des signaux viscéraux, pour lesquels le corps fournit un socle pour la valeur homéostatique ou motivationnelle d'options de choix prédéfinis (Damasio, 1994 ; Bechara, 2004 ; Gu & Fitzgerald, 2014 ; Maniscalco & Rinaman, 2018).

Les conséquences du stress

Le stress aigu peut avoir des conséquences positives en augmentant les performances humaines (De la Torre, 1994) jusqu'à un certain niveau. Cette courbe en U inversée est largement utilisée en pédagogie du stress pour insister sur l'importance de travailler avec un niveau adéquat de stress (Diamond et al., 2007 ; Figure 9). A des niveaux importants de stress aigu, les conséquences peuvent être psychiques (i.e., trouble de stress ; American Psychological Association, 2014) comme physiques. Sur le plan opérationnel, un stress aigu peut entraîner une sidération, voire une mort subite (Frank & Smith, 1990) dont on perçoit bien les risques individuels et collectifs lors de de situations critiques au décours de missions spatiales (Kanas, 1988).

Figure 9
Courbe de stress inversée faisant émerger une relation entre stress et performance
@Barbara Le Roy



Le stress chronique est largement reconnu comme délétère pour la santé (McEwen & Stellar, 1993 ; De la Torre, 1994 ; Stratakis & Chrousos, 1995 ; Zhu et al., 2012). Les missions spatiales sont des environnements de stress chronique. Aux contraintes des environnements ICE/EUE, doit être ajouter les stresseurs sociaux, que la vie de groupe confinée, impliquent et qui font notamment références à des menaces sociales ainsi qu'à des émotions négatives (Martin, 1997 ; Dickerson & Kemeny, 2004 ; Wetherell et al., 2006. La dynamique du stress chronique induit un cercle vicieux de dérégulations et de réponses maladaptées susceptibles d'évoluer indépendamment de la présence des stresseurs chroniques. Geuna et al. (1995) ont proposé une division en trois groupes des conséquences du stress chronique appliquées au vol spatial :

1. Diminution des performances physiques et cognitives : ces dernières peuvent avoir un impact majeur sur l'accomplissement des tâches de la mission, et l'occurrence des erreurs humaines (ESA LTPO-SR-91-01, 1991 ; ESA LTPO-SR-91-04, 1991 ; Levine, 1991).

2. Augmentation de la conflictualité psychologique et interpersonnelle : non discutée dans le cadre de cette présente Thèse, les tensions interpersonnelles sont la résultante de facteurs à la fois environnementaux, individuels et collectifs (Palinkas & Suedfeld, 2008 ; Shepanek, 2005). La littérature a souligné leurs enjeux en vue des prochains longs voyages dans l'espace (Kanas et al., 2013 ; Nicolas et al., 2018).

3. Pathologies psychosomatiques et psychiatriques liées au stress : les missions spatiales précédentes ont rapporté une faible occurrence de troubles psychiques (Kanas, 1987 ; Cooper, 1996) et psychiatriques (Santy, 1987 ; Kanas, 1990), notamment en raison du niveau de sélection des astronautes. Cependant, leur apparition risque d'augmenter à mesure que les distances et temps de mission augmenteront, d'autant plus en raison du rôle de cofacteur que le stress chronique peut jouer.

La théorie de la non-sécurité généralisée du stress

Si le contexte de stresseurs chroniques est le plus souvent évoqué en référence à des stresseurs externes au sujet, des approches récentes soulignent l'importance de considérer les stresseurs internes répétés pour mieux comprendre le stress chronique. La théorie récente de la non-sécurité généralisée du stress (*generalized unsafety theory of* Stress, GUTS) développée par Brosschot et al. (2017) est celle d'un modèle de stress basés sur des postulats suivants : (i) le stress est une réponse par défaut qui est toujours présente dans l'organisme, elle n'est pas générée en réponse à un stresseur mais désinhibée (réponse rigide) dès lors que l'environnement est perçu comme sécure ; (ii) les compétences inhibitrices impliquent les zones préfrontales et la régulation parasympathique pour permettre l'ajustement aux changement de l'environnement ; (iii) les conditions dans lesquelles l'environnement est sécurisant sont apprises par l'organisme au cours de son développement. En miroir, des évènements de vie stressants perturbent les mécanismes inhibiteurs de la réponse de stress ; (iv) le défaut d'inhibition tonique qui fait suite à des stresseurs répétés et/ou intenses conduit à une insécurité généralisée indépendante de la réalité des stresseurs externes (insécurité généralisée). Elle se traduit au niveau de la perception du corps, des relations aux autres et à l'environnement et induit un état de stress chronique avec son risque de complications psychosomatiques.

Brosschot et al. (2017 ; p. 288) notent que « the stress response is a default response of the organism, and that it is the response the organism automatically falls back upon when no other information is available ». Cette théorie prédit comment des réactions de stress prolongées et même chroniques se produisent qu'il y ait ou non des facteurs de stress extérieurs au sujet dès lors que les systèmes d'inhibition du stress sont insuffisants. Il est licite de postuler que les LDSE sont à risques de mettre à mal les freins de contrôle de la réponse de stress par défaut. L'environnement dans lequel les astronautes seront immergés pour une mission martienne est susceptible de porter des conditions de révélation de freins insuffisants qui pour autant étaient efficients avec les stresseurs du quotidien de l'astronaute jusqu'alors.

La contrainte environnementale et la variabilité inter-individuelle des capacités d'adaptation

Les facteurs de stress n'exercent pas la même influence sur tous les individus, une très grande variabilité inter-individuelle existe. L'existence de facteurs de vulnérabilité concomittant avec des variables potentiellement modulatrices, accentueraient ou inhiberaient les effrets néfastes de l'environnement. La réponse pour faire face à ces stresseurs n'est pas identique pour tout le monde (Wood, 1999 ; Clement et al., 2020 ; Strangman et al., 2014). En effet, il n'existe pas une relation linéaire simple du type : stresseur → stress. Chaque individu réagit à un stresseur selon la manière dont il perçoit le risque. Cette perception dépend de nombreux facteurs qu'il est difficile d'isoler. La variabilité inter-individuelle de perception de la contrainte dépend du patrimoine génétique et de l'histoire de l'individu, à laquelle s'ajoute le type de stresseur et ses caractéristiques (i.e., contexte d'apparition, durée, intensité, fréquence de répétition) générant une façon personnelle de réagir au stress. Ce constat pose qu'il existe différentes cibles neurophysiologiques pouvant moduler la réponse de stress.

Tous les environnements extrêmes ont en commun d'imposer des exigences physiques, psychologiques et interpersonnelles de grandes envergures qui nécessitent une adaptation importante de l'espèce humaine pour sa survie et ses performances (Rivolier, 1997).

Le stress inadapté survient lorsqu'un individu est soumis à des exigences qui dépassent, ou menacent de dépasser, sa capacité à faire face. En tant que tel, le stress dépend à la fois de l'environnement et de l'individu (Lazarus, 1966). Plus précisément, c'est la relation stimulus-réponse qui définit le stress. Elle consiste en une évaluation cognitive d'une épreuve vécue comme excédant les ressources disponibles ou pour laquelle aucune réponse n'est possible, mettant en danger son bien-être (Lazarus, 1984). Cependant, le niveau de stress dépend de la capacité de l'individu à faire face à ces exigences, résultants de facteurs tels que les compétences, l'expérience et l'état physique et mental à un instant donné (Lazarus & Folkman, 1984 ; Hughes, 2012). Les facteurs contextuels (e.g., faim, manque de sommeil, environnement social) jouent également un rôle (Lazarus & Folkman, 1984). Même si dans certaines situations, le stress peut nuire à la santé physique et mentale ; dans certains cas il peut être bénéfique, « *eustress* ». L'ensemble de ces approches sont complémentaires.

Carrère (1990) a formulé et testé un modèle dynamique du stress dans les environnements extrêmes en incorporant les modifications dues à l'environnements et aux évènements. Il a proposé trois hypothèses testables :

1. Les individus peuvent s'adapter [et s'adaptent] aux facteurs de stress prévisibles au fil du temps.
2. Les individus ne peuvent pas s'adapter aux facteurs de stress imprévisibles au fil du temps.
3. Les réponses aux facteurs de stress imprévisibles ne seraient pas cumulatives mais spécifiques au niveau du facteur de stress à un moment donné.

Les réponses comportementales et psychologiques que les individus utilisent pour faire face aux facteurs de stress sont souvent appelées stratégies d'adaptation ou coping. La notion de *coping* se réfère à la théorie cognitive du stress et se définit comme un « modérateur des processus qui affectent la relation entre un événement stressant et les ressources dont dispose un individu pour lui faire face » (Fischer & Tarquinio, 2014 ; p. 132). Ces stratégies peuvent être dirigées soit vers le facteur de stress lui-même (adaptation axée sur le problème), soit vers la réponse émotionnelle de l'individu au facteur de stress (adaptation axée sur les émotions). Les stratégies peuvent consister à éviter le facteur de stress, à en atténuer les effets ou à tolérer le stress qui en résulte

(Lazarus & Folkman, 1984). De plus en plus d'études mettent en évidence les effets bénéfiques salutogéniques à long terme d'évoluer en milieu extrême, permettant une meilleure capacité de faire face au stress dans la vie courante mais également d'améliorer l'état de santé et de bien-être (Ritsher et al., 2007).

Cette notion est différente de celle « d'adaptation ». En effet, l'adaptation se définit comme un « processus dynamique de changement lié aux capacités innées ou acquises d'un organisme, d'un individu ou d'un groupe de réagir à des agressions externes ou internes, des contraintes ou des conflits, en cherchant à réduire ou à éliminer leurs conséquences défavorables par des ajustements divers leur permettant de survivre et de créer un nouvel équilibre compatible avec leur survie » (Fischer & Tarquinio, 2014 ; p. 115). En somme, l'adaptation est une notion assez large qui englobe des niveaux très divers de réactions (neurophysiologiques, comportementales, psychologiques, émotionnelles) et qui rend compte de la diversité des réponses que chacun peut apporter aux modifications de l'environnement ou aux changements de son propre organisme. Certains finiront par s'habituer, d'autres ne le feront pas.

Chercher des moyens d'action pour identifier les individus étant les plus à même d'adaptation, et ainsi ayant des ressources efficientes, s'avère dans cette conception plus que nécessaire. Nous avons vu précédemment que le VN contribuait à la modulation du PNS, et ainsi à l'action de frein envers les facteurs de stress. L'étude de la variabilité de la fréquence cardiaque (*heart rate variability*, HRV) offre une opportunité intéressante pour mieux comprendre comment la modulation de l'activité parasympathique peut gérer ces situations et conduire à l'adaptation. Au repos, il s'agit un indicateur d'une arythmie sinusale respiratoire (*respiratory sinus arryhtmia* en anglais) et donc de l'influence du VN sur le cœur (Palma & Benarroch, 2014). La HRV correspond à la variation dans le temps séparant chaque battement cardiaque. En effet, les réponses environnementales sont cohérentes avec les changements d'activité dans les composantes sympathique, parasympathique et entérique du système moteur viscéral qui gouvernent les muscles lisses, le muscle cardiaque et les glandes. Ces systèmes jouent un rôle majeur dans l'équilibre sympathovagal et, par conséquent, contribuent au maintien de l'homéostasie adaptative avec des différences inter-individuelles (Kim et al., 2018a). Ainsi, la variation de la HRV peut refléter la résistance du corps et de l'esprit à un facteur de stress psychologique ou physique, et les biosignaux cardiaques pourraient être un indice de l'adaptabilité du cœur à des conditions environnementales changeantes. La HRV a été validée comme une méthode objective d'évaluation du stress (Thayer et al., 2012) et a été admise comme un facteur de risque cardiovasculaire (Assoumou et al., 2010 ; Schuster et al., 2016 ; Thayer et al., 2010). Ce signal physiologique a été intégré dans l'environnement ICE/EUE (Gifford et al., 2005 ; Lutsenko et al., 2018 ; Maggioni et al., 2020), et dans la recherche militaire (Yuan et al., 2019 ; Hourani et al., 2020). Bien que l'exposition à un environnement extrême semble affecter l'homéostasie et ainsi l'équilibre autonome, Pagani (1995) a montré que l'isolement et le confinement ne paraissent pas modifier le contrôle cardiovasculaire au repos en condition de laboratoire (i.e., fréquence cardiaque, la pression artérielle et mesures temporelles et fréquentielles de la variabilité). Nous pourrions alors nous demander si ce ne sont pas plus les facteurs environnementaux extrêmes en tant que tels qui mèneraient à cette perte.

En nous inscrivant dans ces cadres scientifiques, nous avons l'ambition d'explorer ce terrain encore insuffisamment connu des mécanismes d'adaptation aux environnements singuliers que les missions spatiales imposent. Les différentes approches du stress et de l'adaptation et les études conduites dans ce travail visent à enrichir les cadres d'intervention pour une prévention de la santé en environnement spatial, par une optimisation des mécanismes de l'adaptation.

Adaptation et stress : prévention & technologies

Evidence based-prevention

« *Mens sana in corpore sano* » (« un esprit sain dans un corps sain »), une affirmation élaborée à l'époque de Juvénal qui a traversé les siècles, et qui pour autant n'a jamais eu autant de sens qu'aujourd'hui. Le corps et l'esprit ne semblent pas dissociables mais font véritablement partie d'un tout, d'une unité (Caston, 1993). La recherche a fait de considérables progrès dans l'amélioration des conditions de vie des individus dans un objectif de santé. L'industrie pharmaceutique a souvent été en première ligne de traitements, les interventions moins invasives relayées au second plan. Ces dernières années, l'avènement du progrès technologique a mis en évidence plusieurs approches médicales alternatives à moindre coût, de meilleure qualité et plus accessible pour prévenir les maladies. Le potentiel dans ce cadre de *l'évidence based-prevention* n'est plus à démontrer (Pentz, 2003).

Un des enjeux majeurs des missions spatiales de demain repose sur la mise en œuvre de contre-mesures efficientes pour maintenir la santé et les performances des individus. Ce besoin est particulièrement prégnant dans les professions à risque telles que celles des astronautes, notamment à mesure de l'allongement de la durée et de la situation géographique des missions. Jennifer Fogarty (Fogarty, 2009 ; p. 9) a défini les contre-mesures comme « une action, un processus, un dispositif ou un système qui peut prévenir ou atténuer (annuler ou compenser) les effets des menaces pesant sur un être humain ; une menace est un événement indésirable potentiel ou réel qui peut être malveillant ou accidentel et qui peut compromettre la santé et/ou les performances d'un individu et l'intégrité de la mission ». Les méthodes d'intervention à visée de contre-mesures préventives doivent, pour être le plus ajustées, veiller et être au plus près des individus pour maintenir leur santé. Actuellement, les astronautes sont hautement sélectionnés et suivis avant, pendant et après chaque mission. Pour autant, l'hypothèse d'un voyage martien, de stations spatiales pérennes comme d'un tourisme spatial de masse réinterrogent les besoins de promotion de la santé. Plusieurs cibles de prévention sont à envisager dans le cadre de la prévention des effets délétères liés aux contraintes de l'exposition à ce type de missions spatiales.

Au sein de ce travail, il s'agit de cibler la question de la prévention de la mal-adaptation de l'individu. Au décours d'une mission spatiale, de nombreux autres enjeux de prévention et de maintien de la santé existent et les conditions d'exercer la médecine et la chirurgie lors des LDSE font l'objet de nombreuses études prospectives (Wohrer, 2021). Lorsque l'on s'intéresse à la prévention d'une mal-adaptation individuelle de la préparation de la mission, de sa réalisation et de sa récupération, plusieurs axes de recherche doivent être interrogés ; ces axes se rejoignent pour certains mécanismes mais ne se superposent pas. Il existe des actions de prévention déjà identifiées pour certains mécanismes. Néanmoins, leurs mises en œuvre dans le cadre des missions spatiales de demain doivent faire l'objet de validation et d'autres actions prophylactiques sont à proposer et à évaluer au regard des avancées récentes de la science.

Le premier axe de prévention questionne l'identification des facteurs de risque de mal-adaptation *per se*. Dans la littérature, on retrouve deux types de facteurs prédictifs qui, s'ils peuvent se recouper, ne doivent pas se confondre : les facteurs de vulnérabilité et les facteurs de risque. La vulnérabilité représente un continuum entre le neurotypique et le pathologique. Ce continuum favorise l'entrée dans une pathologie si l'environnement surcharge la capacité de fonctionnement de l'individu (Ingram & Price, 2001). Cette capacité de fonctionnement est dépendante de l'ontogenèse des individus (i.e., génétique, épigénétique, histoire de vie). Les facteurs de risques représentent un état des lieux instantané du risque encouru par le patient. Ces facteurs de risques peuvent être endogènes ou exogènes et relèvent de l'épidémiologie, soit la corrélation entre un phénomène et la fréquence d'un trouble dans une population donnée. Leurs prédictions ne sont pas à valeur individuelle. Ainsi, en considérant la question du risque de mal-adaptation, il est possible d'identifier actuellement certains facteurs de risque statistiques à partir d'études menées au sein des analogues spatiaux afin de proposer des actions de prévention ciblant ces facteurs de risque.

Le second axe est une prévention visant à favoriser une réaction d'*eustress* et réduire le risque de *distress* face aux aléas aigus de la mission durant la mission. Cet axe implique de suivre les équipages durant l'intégralité de leur mission afin d'étudier les processus internes à l'œuvre. La détection à un instant T d'un certain degré ou d'un changement des indicateurs de santé (e.g., fatigue, humeur, stress, performance) et de risque (e.g., vigilance) a le potentiel de mettre en évidence la capacité d'un individu à réguler son état mais également les trajectoires qu'il emprunte pour y arriver. Cela sous-entend en amont une prise en compte fine des facteurs en jeu dans l'adaptation.

Le troisième axe cible la réduction du risque de dérive de l'exposition cumulée aux stresseurs de la mission. Une exposition prolongée aux facteurs de stress et/ou une activation prolongée même lorsque les facteurs de stress ne sont plus présents entraînent des changements psychophysiologiques plus permanents. Ceux-ci nuisent au fonctionnement de l'individu car l'organisme considère l'état de stress comme le nouveau référentiel (Selye, 1955). Le temps passant, ces changements psychophysiologiques diminuent la capacité d'un individu à faire face à de futurs facteurs de stress. Une accumulation de stresseurs augmente ainsi le risque de dévier vers un état de vulnérabilité. Il s'agit donc de favoriser un comportement adaptatif de qualité et dans la durée notamment en développant et/ou renforçant les capacités à la fois de régulation psychophysiologiques du stress, des émotions, et cognitives. Ainsi, l'exigence imposée des missions implique aux équipages une régulation autonome d'eux-mêmes entre les exigences environnementales, professionnelles et personnelles. Ces dernières impliquent qu'ils soient dans un état d'hypervigilance constant pour être prêt à faire face à toute éventualité. Habiter un milieu non écologique pour l'être humain implique de gommer la frontière entre l'univers professionnel et personnel (e.g., entretien, gestion des incidents, exercices). Les situations qui en découlent augmentent le facteur de risque d'un état critique de l'équipage, d'autant que celui-ci est intégralement autonome. Le danger peut survenir de nulle part, le *corps* [ensemble] doit faire front en gérant à la fois la charge qu'incombe le nouvel environnement et l'imprévu. Les actions de prévention doivent idéalement se cibler au plus près l'individu.

Enfin, la cible de la prévention de la récupération doit être envisagée. Celle-ci est indissociable d'une inscription dans la durée. La récupération doit être envisagée à deux niveaux : (1) au cours de la mission, (2) en post mission. En effet, l'habitat constituant à la fois le lieu de vie de professionnel et personnel, ce dernier peut constituer une entrave à la récupération (Searle, 2012). La recherche en a montré les limites au détriment d'un détachement psychologique. Également, suivre les équipages sur une période suffisamment longue au retour de mission est primordial pour pouvoir évaluer et appréhender l'enjeu de la récupération. Plusieurs facteurs sont à prendre en compte tels que l'intensité de la mission précédente, l'intensité prévue de la mission suivante et la vie professionnelle entre les missions (Castro & Adler, 1999).

Afin d'apporter des éléments de réponse appropriés, l'objectif de ce travail n'est en rien de transposer des outils existants sans étudier à la fois la singularité des individus des milieux extrêmes actuels, en ouvrant à ceux du futur, mais aussi les facettes psycho-physio-cognitivo-sensorielles que ces environnements challengent. Proposer des contre-mesures efficaces est sans nul doute notre première ambition mais de manière juste et raisonnée en se basant sur la prise en compte des besoins identifiés par des études en amont de professionnels exposés à des contraintes dans des analogues spatiaux afin que le bénéfice en soit d'autant plus important. Les interventions les plus efficaces se construisent au croisement de l'expertise clinique individuelle et de l'utilisation consciencieuse, explicite et judicieuse des meilleures preuves d'efficacité qui concernent le patient ou la population ciblée (Sackett & Larson, 1990 ; Thurin, 2006) en intégrant la prise en compte des spécificités culturelles et le contexte d'implémentation (Reese & Vera, 2007 ; American Psychological Association, 2014 ; Gottfredson et al*.,* 2015). Le cadre de référence fournit par *l'evidence based-prevention* recommande d'intégrer une évaluation systématique des interventions, à savoir déterminer si les objectifs ont été atteints avec la mise en place des interventions pour garantir l'efficacité des approches concernées (American Psychological Association, 2014 ; Schwartz & Hage, 2009 ; Vera et al., 2009 ; Vera, 2020).

Nous proposons dans la continuité de ce cadre de prise en compte de la prévention de faire un tour d'horizon des champs de prévention croisant médecine et technologies pour ouvrir les actions de prévention à la médecine de demain.

1. Un monde immersif sans limite

L'innovation est omniprésente autour de nous, et plus particulièrement dans le monde de la santé. Elle est un vecteur d'amélioration et de personnalisation des soins et donc de la santé au plus près des individus. Les expériences immersives ouvrent un monde nouveau et peuvent notamment maintenir et améliorer les liens sociaux et les compétences interpersonnelles même à des milliers de kilomètres. Également, les facteurs de stress liés à l'environnement physique pourraient être atténués par des expériences conçues de manière stratégique dans des environnements immersifs permettant de repousser les frontières du réel, offrant ainsi aux individus un espace sans délimitation. Ces dernières années, la réalité virtuelle (*virtual reality*, VR) a été reconnue comme une nouvelle approche de la promotion de la santé (Bin et al., 2020 ; Li et al., 2017 ; Stubbs et al., 2017) qui permet de relier le corps et l'esprit (Riva et al., 2017). Le terme VR a été utilisé pour la première fois par Jaron Lamier en 1986. Ce pionnier de la VR fait référence à une interface de communication technologique avancée dans laquelle l'utilisateur interagit efficacement avec un monde virtuel tridimensionnel généré par un ordinateur pour simuler des expériences du monde réel (Malbos, 2015 ; Maples-Keler et al., 2017a). Les trackers détectent la position et l'orientation de l'utilisateur et transmettent ces informations à l'ordinateur qui met à jour en temps réel les images à afficher, ce qui permet à l'utilisateur d'explorer et d'être immergé dans l'environnement virtuel. Les projections VR intègrent également une stimulation visuelle, auditive et parfois tactile pour renforcer la perception de son corps dans l'environnement virtuel. Cet outil nous offre un moyen de simuler la réalité et de stimuler les sens du corps avec pour seule limite l'imagination humaine (Figure 10). La VR opère donc dans un nouvel espace-temps façonné de toutes pièces à mi-chemin entre le réel et l'irréel, repoussant les limites de la réalité et expérimentant de nouveaux paradigmes auxquels nous n'aurions pas eu accès autrement.

Figure 10
Expérience immersive VR « Time travel » proposée par Virtual Room Bogota

La littérature a mis en évidence la valeur de l'utilisation de la VR comme outil thérapeutique pour traiter les troubles mentaux tels que l'anxiété, la dépression, le trouble de stress post-traumatique (*post-traumatic stress disorder*, PTSD) et les phobies (Andrews et al., 2020 ; Firth et al., 2018 ; Freeman et al., 2017 ; Gerardi et al., 2020 ; Kim & Kim, 2020 ; Maples-Keller et al., 2017a ; Maples-Keller et al., 2017b ; Nason et al., 2019 ; Oing & Prescott, 2018 ; Page & Coxon, 2017 ; Parsons & Rizzo, 2008 ; Riva et al., 2019). Les antidépresseurs, tels que les inhibiteurs sélectifs de la recapture de la sérotonine, les inhibiteurs de la recapture de la sérotonine et de la norépinéphrine, ou les benzodiazépines sont le traitement de première intention des symptômes d'anxiété chez les patients, tandis que la thérapie cognitivo-comportementale s'est avérée efficace pour les réduire (Bandelow, 2020 ; Bernier & Simard, 2007 ; Cieślik et al., 2020). La VR offre ainsi une option non médicamenteuse nouvelle et innovante pour les personnes dont les traitements sont souvent lourds et ont des effets secondaires. Les interventions de VR, telles que les thérapies d'exposition à la réalité virtuelle (*virtual reality exposure therapy*, VRET), se sont avérées efficaces en tant que traitement coadjuvant dans les maladies mentales. Les VRET semblent avoir les mêmes effets que les traitements médicamenteux, bien que les résultats prennent plus de temps à se manifester (Kim & Kim, 2020). Cependant, bien que le manque d'études longitudinales ne permette pas de savoir si ces effets sont maintenus à long terme, quelques études ont trouvé que les réductions significatives des symptômes étaient maintenues lors des sessions de suivi à 6 mois (Fernández-Álvarez et al., 2020 ; Maples-Keller et al., 2017b ; Rothbaum et al., 2001). Une revue de Landowska et al. (2017) a souligné que la base neuronale de la VRET, et ses effets sur l'activité cérébrale sont peu documentés. Cette même étude a souligné le rôle essentiel du PFC dans la VRET, plus précisément du PFC dorsolatéral et du PFC médian. Cette cible renvoie au rôle du frein de cette zone préfrontale que Brosschot et al. (2018) identifient comme essentiel pour prévenir du risque de syndrome d'insécurité généralisé dans son modèle de stress (i.e., GUTS). Ceci est en accord avec de nombreuses études qui démontrent des effets et des mécanismes similaires en utilisant des thérapies d'exposition traditionnelles (Anderson & Mollloy, 2020 ; Lognoul et al., 2020). Utilisée comme une thérapie complémentaire, la VR peut avoir de nombreux avantages, notamment la capacité de recréer un environnement traumatique réaliste dans des conditions contrôlées, ce qui peut être complexe in vivo (Maples-Keller et al., 2017b ; Slater et al., 2010 ; Spanlang et al., 2014).

Cependant, la VR va au-delà de la représentation et de la simulation du monde extérieur. Ces dernières années, les recherches de Riva et collaborateurs ont mis en évidence le concept de l'« *embodied virtual medicine* » (Riva et al., 2017 ; Riva et al., 2019). Ce terme de plus en plus utilisé indique que la VR pourrait permettre de modifier la perception de soi, de son corps et donc de l'incarnation au sens de la représentation du corps. La modulation des informations intéroceptives, extéroceptives et vestibulaires conduit à une représentation de notre propre corps, un symbole de la perception (Riva, 2018). Cette conceptualisation multisensorielle a développé la « matrice corporelle » (*body matrix* en anglais) qui fait référence aux limites du corps. En d'autres termes, il s'agit d'une protection du corps qui sert de médiateur entre le monde interne (i.e., le nôtre) et le monde externe (i.e., l'espace qui nous entoure) avec une capacité d'évolution qui conduit à l'adaptation. La VR permet de générer chez l'être humain l'illusion d'être et de se déplacer dans un corps alternatif. Ce concept théorique décrit l'« *embodiement* » comme un état dans lequel les expériences des utilisateurs sont intercalées par des dispositifs technologiques qui s'entremêlent avec leur corps et leur permettent de percevoir, d'interpréter et d'interagir avec leur environnement perçu à travers une représentation interne de ce corps (Tussyadiah et al., 2018). Kilteni et al. (2012) ont défini le sens de l'*embodiement* envers un corps comme « le sentiment qui émerge lorsque les propriétés du corps sont traitées comme si elles étaient les propriétés de son propre corps biologique ». Ils ont montré que la VR pouvait être un outil efficace pour manipuler l'*embodiement*. Plus précisément, trois catégories sont impliquées dans ce processus, à savoir le sens de la localisation, la propriété du corps et le sens de l'agentivité. Le sens de la localisation (*location* en anglais) se réfère à « l'expérience spatiale d'être à l'intérieur d'un corps et ne se réfère pas à l'expérience spatiale d'être à l'intérieur d'un monde », tandis que le sens de la propriété du corps (*body ownership* en anglais) est « l'auto-attribution d'un corps », et le sens de l'agentivité (*agency* en anglais) est « le contrôle moteur global, y compris l'expérience subjective de l'action, du contrôle, de l'intention, de la sélection du moteur et l'expérience consciente de la volonté » (Kilteni et al., 2012 ; Blanke & Metzinger, 2009). Grâce à la VR, il est possible d'induire l'illusion d'être et de se déplacer dans un faux corps. Cet interstice leur permet de percevoir, d'interpréter et d'interagir avec leur environnement perçu à travers une représentation interne du monde (Riva, 2018). Ainsi, l'expérience dans un environnement de VR peut conduire à changer la *body matrix* et à avoir un impact sur le sens de l'*embodiement* dans l'état de la VR. La répétition de la pratique de la VR peut stimuler des changements cérébraux fondés sur les mécanismes de neuroplasticité (Cheung et al., 2014). En accord avec la littérature (Riva et al., 2017), un tel effet peut être d'autant plus important que la tendance à l'immersion est élevée et que l'état de présence pendant l'expérience de VR est élevé. Enfin, l'immersion est définie comme « l'illusion » que « la technologie de l'environnement virtuel remplace les stimuli sensoriels de l'utilisateur par les stimuli sensoriels virtuels ». Cette illusion est plus facile pour les sujets ayant une forte tendance à être immergés (i.e., capacité de tendance à l'immersion). L'expérience immersive dépend également de la présence pendant l'expérience VR, c'est-à-dire du « sentiment d'être là » (i.e., « *being there* ») de l'utilisateur dans cet environnement (Jennette et al., 2008 ; Johns et al., 2000). De plus, l'intégration multisensorielle dans la VR permet de générer ce sentiment d' « être là », et donc l'illusion d'être dans un corps alternatif. Slater (2009) a défini la présence comme « la forte illusion d'être dans un endroit malgré la certitude que vous n'y êtes pas ». Le véritable pouvoir de la VR est d'aller au-delà de ce qui est réel en donnant un sentiment de réalité dans l'irréel, en modifiant la perception. C'est la raison pour laquelle un sujet a le sentiment d'être dans un environnement virtuel alors qu'il sait consciemment qu'il n'y est pas et que ce corps virtuel est le sien. Tuena et al. (2017) ont montré l'implication de l'incarnation dans le sentiment de présence. Plus précisément, ils corroborent les résultats avancés par Riva (2008) selon lesquels il s'agit de concepts complémentaires à la représentation du corps et de l'espace qui l'entoure. La présence est également liée au flow qui se définit par « la sensation holistique que les gens ressentent lorsqu'ils agissent avec une implication totale » (Csikszentmihalyi, 1975). Il s'agit donc d'un état psychologique impliquant le plaisir, l'absorption cognitive et la distorsion du temps/de la perception. La littérature sur la VR a souligné la contribution de la présence et du flux dans l'immersion (Shin, 2017 ; Weibel et al., 2011).

La VR constituerait donc un média prometteur pour promouvoir la santé.

La plupart des études montrent que les participants ont un degré élevé d'acceptation envers la technologie. Son utilisation est cohérente avec les améliorations post-intervention de la conscience des symptômes, une diminution des symptômes dépressifs, une plus grande motivation à faire de l'exercice, et un meilleur plaisir, engagement et affect, en particulier dans les populations cliniques (Firth et al., 2018 ; Gerardi et al., 2010 ; Nason et al., 2019 ; Oing & Prescott, 2018). La VR peut stimuler l'émotion (notamment la peur), par le sentiment de présence (irréel) que génère cette technologie immersive (Riva et al., 2007 ; Slater, 2018). Ainsi, elle apparaît comme un complément non médicamenteux innovant à d'autres traitements qui peuvent être exigeants pour le patient et avoir des effets secondaires. Bien que la qualité de la technologie puisse jouer un rôle dans les résultats positifs (Roche et al., 2019), elle semble être un nouvel outil prometteur qui ne présente aucune menace sérieuse pour les participants (Matamala-Gomez et al., 2018).

2. *L'activité physique pour un maintien de santé*

Historiquement, il semble intuitif que l'activité physique soit importante pour préserver la santé des individus et les protéger de nombreuses pathologies (Biddle et al., 2000 ; Blair et al., 1989 ; Kohl et al., 1992 ; Plante et al., 2001 ; Schaie et al., 2002 ; Winett & Carpinelli, 2000). Elle peut être définie comme « tout mouvement corporel produit par les muscles squelettiques qui entraîne une dépense d'énergie supérieure au métabolisme de repos » (HAS, 2019). L'une des composantes de l'activité physique est l'exercice physique, entendu comme « une activité physique planifiée, structurée et répétitive dont l'objectif est d'améliorer ou de maintenir une ou plusieurs composantes de la condition physique » (HAS, 2019). Depuis de nombreuses années, la littérature montre les bénéfices de l'activité physique sur la santé, tant physique (i.e., réduction du taux de mortalité, réduction du risque de pathologies cardiovasculaires, réduction de l'incidence du cancer, maintien du statut pondéral) et cognitive (amélioration des fonctions cognitives, amélioration du sommeil, réduction du risque de démence), que psychologique (i.e., réduction des signes d'anxiété et de dépression, réduction du risque de dépression), dans la population générale (adultes, enfants et personnes âgées), et pour diverses maladies chroniques et états de santé (Biddle et al., 2000 ; Blair et al., 1989 ; Conn, 2010 ; Kohl et al., 1992 ; Plante et al., 2001 ; Martinsen, 2008 ; Schaie et al., 2002 ; Ströhle, 2009 ; Winett et al., 2000). Ce n'est que récemment que la communauté scientifique a commencé à s'intéresser aux raisons et mécanismes biologiques et physiologiques permettant d'arriver à de telles conclusions (Ratey & Loehr, 2011 ; Rebar et al., 2015 ; Ströhle, 2019). L'exercice physique d'intensité modérée semble avoir un effet à court terme sur les états anxieux dans des populations non pathologiques ou pathologiques et peut être utilisé pour réduire cette expérience (Inserm, 2008). L'activité physique peut jouer un rôle majeur pour limiter l'inadaptation et ainsi améliorer la qualité de vie des patients. L'exercice aérobie régulier est associé à une diminution de la réactivité du SNS et de l'axe hypothalamo-hypophyso-surrénalien, à l'exercice d'un contrôle sur ses émotions (i.e., diminution de la détresse émotionnelle), à l'amélioration de la relaxation, à l'induction d'un sentiment d'auto-efficacité et à la réduction des symptômes dépressifs dans les populations non cliniques et cliniques et dans la dépression majeure (Anderson & Shivakumar, 2013 ; Conn, 2010 ; Inserm, 2008 ; Martinsen, 2008 ; Ströhle, 2019 ; Wu et al., 2017). Cependant, la pratique d'une activité physique peut avoir des dérives réduisant les bénéfices de son action, notamment par une pratique addictive ou inadaptée à certaines pathologies (Hausenblas & Downs, 2002 ; Kern et al., 2019 ; Martin-Krumm & Tarquinio, 2024). Hausenblas et al. (2001) soulignent que les recherches montrent que l'exercice physique peut être associé à différents traitements pharmacologiques (neuroleptiques, antidépresseurs) et qu'il agit davantage en synergie qu'en opposition. L'activité physique est un adjuvant aux traitements conventionnels des troubles mentaux (Callaghan, 2004 ; WHO, 2000) permettant une réduction des symptômes, une réduction des pathologies associées, le développement de stratégies d'adaptation (coping), la réduction du stress, la compensation des effets secondaires des traitements médicamenteux). De plus, le traitement sensoriel et la perception sont liés à la santé mentale et les personnes atteintes de maladies mentales présentent très souvent des perturbations du traitement sensoriel et de la perception (McKinnon et al., 2016). Une thérapie sportive optimisée de la prévention et du traitement des troubles mentaux doit se concentrer sur la modalité de la pratique sportive.

Il semble pertinent de travailler sur les conditions globales de l'entraînement sportif en tant que contre-mesure clé, et d'augmenter l'adhésion à celui-ci. Une activité physique régulière est nécessaire pour une gestion optimale des maladies mentales. Elle constitue une composante essentielle de la vie quotidienne d'un astronaute en mission à bord de l'ISS. Selon la NASA, les astronautes devraient s'entraîner chaque jour en moyenne deux heures et demie quand ils sont dans l'espace afin de diminuer les effets de la microgravité sur les os, les muscles du corps, l'activité cardiaque, mener des procédures d'urgence et maintenir leur santé. En conséquence, l'activité physique sportive est la contre-mesure de premier plan à bord de la station spatiale internationale (*international space station*, ISS) (Doarn et al., 2019 ; Fraser et al., 2012 ; Hackney et al., 2015 ; Reynolds & Day, 2010 ; Smith & Raab, 1986). Toutefois, s'il s'agit de la première intervention pour limiter les effets négatifs induits par la vie en microgravité. Force est de constater que les conditions de la pratique ne sont pas de nature *a priori* à soutenir la satisfaction des besoins fondamentaux selon la théorie de l'autodétermination (Ryan & Deci, 2017) que sont le besoin de proximité sociale (i.e., les relations sont limitées à celles avec les membres de l'équipage), le besoin d'autonomie (i.e., inévitablement limité compte-tenu de l'hostilité de l'environnement) et le besoin d'accomplissement (e.g., les progrès en termes d'activité physique sont limités dans cet environnement). Au-delà même du maintien d'une motivation de qualité, la satisfaction des besoins fondamentaux est déterminante pour le bien-être et l'épanouissement des individus (Sarrazin et al., 2011). Par ailleurs, nous avons pu observer lors des missions de longue durée en sous-marin que la quantité de pratique d'une activité physique était un indicateur de l'état d'adaptation extéroceptive et de récupération des sous-mariniers mais non suffisante pour contrebalancer la dégradation thymique au cours de la mission (Martin-Krumm et al., 2021). Dès lors, l'entretien de la motivation des astronautes à pratiquer une activité physique sur le long terme à bord pourrait s'avérer problématique alors qu'elle est cruciale. Force est donc de constater qu'avoir accès à des dispositifs soutenant la pratique est un atout déterminant pour contrebalancer la frustration potentielle des besoins fondamentaux. L'apport de la réalité virtuelle peut s'avérer bénéfique d'autant qu'elle est susceptible d'engager les pratiquant dans un état de flow considéré comme prédisant la persistance du comportement (Fenouillet, 2012 ; Heutte, 2018).

La VR associée à l'activité physique sportive a été peu étudiée dans la littérature. Les premières études pionnières sur le sujet ont été réalisées par Plante et al. (2003a, 2003b, 2006). Ces dernières semblent démontrer de réels avantages en termes de bien-être, en particulier chez les femmes (Plante et al., 2003a). L'ajout de la VR a renforcé les avantages de l'humeur, augmenté le plaisir et l'énergie, réduit la fatigue, amélioré la motivation et la confiance, sans parler de la conformité (Plante et al., 2003a ; Thornton et al., 2005). Le plaisir autotélique peut jouer un rôle important dans les avantages tirés de l'exercice (Plante et al., 2003a). Ces dernières années, le nombre d'études encourageant la pratique du sport pour prévenir les troubles anxieux et protéger contre l'anxiété et la dépression a augmenté (Qian et al., 2020 ; Zeng et al., 2018). Une étude de 2020 a démontré son importance dans le contexte de la pandémie de COVID-19. Elle a permis d'améliorer le bien-être grâce à de meilleurs résultats physiques et cognitifs, et de limiter les troubles psychologiques liés à l'isolement et au confinement (Gao et al., 2020). Ainsi, la littérature suggère que la VR couplée à l'activité physique peut être un moyen utile d'améliorer la symptomatologie des individus souffrant de troubles anxieux, du PTSD et de dépression (Gao et al., 2020).

Lors de sa dernière mission spatiale Alpha, l'astronaute français Thomas Pesquet s'entrainait sur un dispositif immersif associant activité physique et VR développé par la start-up Fit Immersion, spécialisée dans les entraînements sportifs (Photographie 8).

Photographie 8
Essai de l'ergocycle immersif par Thomas Pesquet avant son décollage (2011)

Outre l'*embodied virtual medicine*, une des pistes de prévention prometteuse est représentée par le renforcement du tonus vagal.

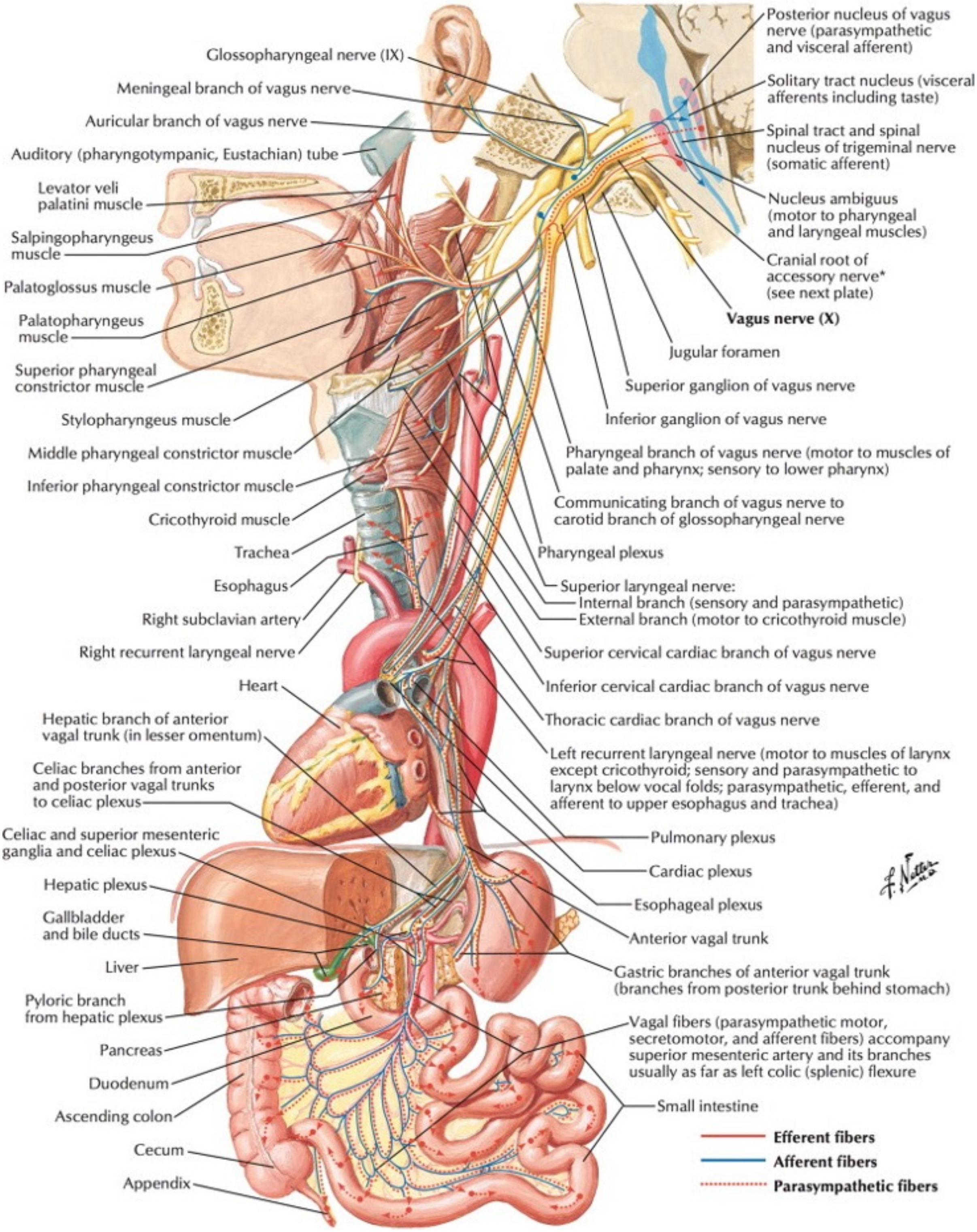
3. *Le potentiel du nerf vague comme reflet de l'homéostasie de l'organisme*

L'implication du VN dans la santé est particulièrement bien étudiée en clinique avec des résultats très prometteurs. Ce dernier via le PNS amortit la réponse physiologique en fonctionnement comme un frein, en inhibant le SNS. Son rôle pour répondre aux enjeux de santé et de prévention s'avère fondamental. Pour autant dans le champ de la prévention du stress chez le sujet sain, il demande encore à être davantage exploré. Les enjeux concernent notamment la mesure de son fonctionnement afin de pouvoir évaluer les outils visant au renforcement de son fonctionnement. Le système vagal largement impliqué dans la régulation autonome de la HRV, de la fréquence cardiaque et de la pression artérielle n'est plus à redéfinir (Capilupi et al., 2019 ; Karemaker, 2015). Son faible coût et sa mise en pratique en font une sélection de premier choix comparativement aux biomarqueurs basés sur l'imagerie par résonance magnétique fonctionnelle (*functional magnetic resonance imaging*, fMRI) (Mithani et al., 2019 ; Yakunina et al., 2017). En effet, l'activité du VN efférent peut être mesurée de manière non invasive par la HRV et plus particulièrement, par la moyenne quadratique des différences successives (*root mean square of differences between adjacent RR* intervals, RMSSD) et la bande des hautes fréquences (*high frequency*, HF). Physiologiquement, l'augmentation de l'activité efférente du VN entraîne un ralentissement de la fréquence cardiaque, via l'inhibition du nœud sinusal par la libération d'acétylcholine (Laborde et al., 2017 ; Task Force, 1996). Étant donné que le signal de la stimulation vagale transcutanée auriculaire (*transcutaneous auricular vagus nerve stimulation*, taVNS) est envoyé par voie afférente au cortex préfrontal via la branche auriculaire du nerf vague (*auricular branch of the vagus nerve*, ABVN), l'activité vagale cardiaque pourrait être affectée par la stimulation vagale (Murray et al., 2016). Cependant, en utilisant le RMSSD pour mesurer l'effet de la taVNS sur l'activité vagale cardiaque, différentes études n'ont pas trouvé de différences entre la stimulation active et la stimulation placebo *sham* (Burger et al., 2016 ; Burger et al., 2019 ; De Couck et al., 2017 ; Borges et al., 2019). Pour autant, Clancy et al. (2014) ont évalué la taVNS sur les effets de l'ANS. Ils ont montré que la taVNS augmentait la HRV chez les sujets neurotypiques, indiquant un changement de la fonction autonome cardiaque vers une prédominance parasympathique. Les enregistrements microneurographiques ont également révélé une diminution significative de la fréquence et de l'incidence de l'activité du nerf sympathique musculaire pendant la taVNS. Récemment, Machetanz et al. (2021a) ont mis en évidence que le RMSSD, deviation standard de la variabilité instantannée des intervalles RR à court terme (*standard deviation of instantaneous short-term RR variability*, SD1) et la deviation standard de l'intervalle RR (*standard deviation of normal-to-normal RR interval*, SDNN) pourraient être des biomarqueurs particulièrement adaptés à l'adaptation du taVNS. Egalement, ils ont montré une diminution de la HRV lors de la stimulation du cavum conchae. Dans une autre étude, Machetanz et al. (2021b) ont confirmé une diminution de la HRV lors de la stimulation du cavum conchae. Ainsi, les mesures par électrocardiogramme (*electrocardiogram*, ECG) sont considérées comme l'un des biomarqueurs les plus prometteurs pour définir des paramètres mécanistiques cibles optimaux de la taVNS (Clancy et al., 2014 ; Gurel et al., 2020 ; Machetanz et al., 2021a ; Machetanz et al., 2021b).

3.1. Anatomie du nerf vague

Le VN (nerf crânien X) est le nerf des arcs pharyngiens (branchiaux) 4 et 6. Encore appelé « nerf pneumogastrique », il est le plus long de tous les nerfs crâniens. Il quitte le tronc cérébral par le sillon rétro-olivaire et le crâne par le foramen jugulaire avec les nerfs IX et XI, chemine entre la veine jugulaire et l'artère carotide vers le larynx, l'œsophage, la trachée, le cœur et le système gastro-intestinal (Figure 11).

Figure 11
Schéma anatomique du nerf vague (Netter, 2007)



Le VN est un nerf :

- Afférent somatique général : innerve la dure-mère infratentorielle, l'oreille externe, le méat acoustique externe et la membrane du tympan. Ses corps cellulaires se situent dans la région du ganglion supérieur et il projette ses prolongements centraux sur le tractus spinal et le noyau du nerf trijumeau.
- Afférent viscéral général : innerve les muqueuses du pharynx, du larynx, de l'œsophage, de la trachée et des viscères thoraciques et abdominaux (jusqu'à la moitié du colon transverse). Ses corps cellulaires se trouvent dans le ganglion inférieur et il projette ses prolongements au tractus solitaire et au noyau correspondant.
- Afférent viscéral spécial : innerve les bourgeons gustatifs de la région de l'épiglotte. Ses corps cellulaires se trouvent dans le ganglion inférieur et il projette ses prolongements centraux vers le tractus et le noyau solitaire.
- Efférent viscéral général : innerve les muscles du pharynx et du larynx dérivés des arcs pharyngiens (brachiaux), la musculature striée de la région supérieure de l'œsophage, les muscles uvulaires, élévateur du voile du palais et palatoglosse. Il provient du noyau ambigu dans la région latérale de la moelle allongée. La composante efférente viscéral générale fournit la composante efférente du réflexe de bâillement.
- Efférent viscéral spécial : innerve les viscères du cou et des cavités thoracique (cœur) et abdominale jusqu'au milieu du colon transverse. Les neurones parasympathiques préganglionnaires se trouvant dans le noyau moteur dorsal de la moelle allongée se projettent sur les ganglions terminaux des viscères.

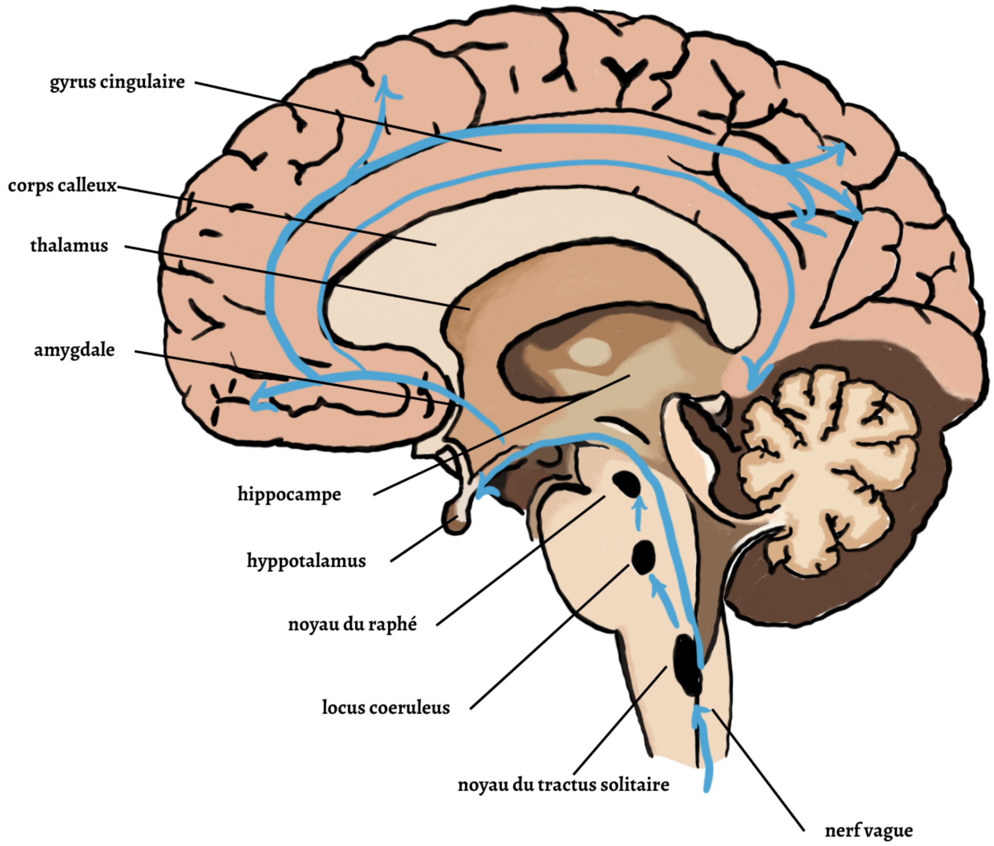
Il est constitué en majorité de fibres afférentes (80% dans sa portion cervicale) provenant des poumons, du cœur, de l'aorte et du tractus gastro-intestinal mais également de fibres efférentes parasympathiques et somatomotrices innervant les muscles striés du pharynx, du larynx et les viscères thoracoabdominaux. Il assure la phonation, la déglutition avec les nerfs IX, XI, XII, l'élévation du voile du palais, la perception du goût et la sensation cutanée de l'oreille. Il innerve également les viscères du cou, du thorax et de l'abdomen.

3.2. Régions cérébrales impliquées

Les VNs droit et gauche sortent du tronc cérébral et traversent le cou (dans la gaine carotidienne, entre l'artère carotide et la veine jugulaire), la partie supérieure de la poitrine (le long de la trachée), la partie inférieure de la poitrine et le diaphragme (le long de l'œsophage), puis la cavité abdominale (Krahl, 2012). Au cours de ce parcours, des branches innervent diverses structures telles que le larynx, le pharynx, le cœur, les poumons et le tractus gastro-intestinal. Les deux branches du VN sont asymétriques dans leurs efférences cardiovasculaires qui régulent la fréquence cardiaque et la pression sanguine. La branche gauche innerve les ventricules tandis que la branche droite innerve densément les oreillettes. Il s'agit d'une des raisons pour laquelle, historiquement la stimulation du nerf vague (*vagus nerve stimulation*, VNS) est pratiquée sur le VN gauche. Sa justification initiale était l'évitement d'éventuels effets indésirables sur le rythme cardiaque. Toutefois, il n'existe à ce jour aucune preuve empirique clinique.

Dans le tronc cérébral, les fibres afférentes sensorielles se terminent dans le noyaux du tractus solitaire (*nucleus tractus solitarius*, NTS) (i.e., noyau solitaire), qui envoie ensuite des fibres qui se connectent directement ou indirectement à différentes régions du cerveau dont le cortex préfrontal qui joue un rôle important dans la régulation émotionnelle. Ces régions comprennent les noyaux du raphé dorsal, le locus cœruleus, l'amygdale, l'hypothalamus, le thalamus et le cortex orbitofrontal (Figure 12).

Figure 12
Projection des afférences vagales
©Barbara le Roy



Le VN a été largement étudié chez les animaux et les humains pour comprendre son rôle dans la physiologie et le comportement, et plus récemment, pour comprendre le rôle du système vagal afférent dans les processus perceptifs et psychologiques (Yuan & Silberstein, 2016a, 2016b, 2016c). Il est en particulier impliqué dans la régulation du PNS en modulant sa fonction à la périphérie et en agissant comme balance du SNS. Sa composante afférente (i.e., sensorielle) et efférente prédominante (i.e., motrice) jouent un rôle important dans le maintien de l'homéostasie (Yuan & Silberstein, 2016a, 2016b, 2016c). L'acétylcholine est le principal neurotransmetteur du VN. Elle active les récepteurs cholinergiques qui sont subdivisés en récepteurs nicotiniques et muscariniques. Les effets principaux induits peuvent entraîner une bradycardie, une augmentation des sécrétions salivaire, gastrique et intestinale, une augmentation du péristaltisme intestinal, et un relâchement des sphincters et myosis.

Le VN est composé de différents types de fibres dont la myélinisation, la taille et la vitesse de conduction varient. Trois types de fibres A, B et C ont été identifiés, chacune ayant des propriétés physiologiques propres (i.e., différents seuils d'excitation en réponse à un stimulus). Cependant, il est communément admis que plus la taille de la fibre est importante, plus la vitesse de conduction sera rapide. Les fibres vagales de type A (Aα Aβ, Aγ et Aδ), ayant un diamètre important de 1–22 µm et fortement myélinisées, sont composées de fibres afférentes viscérales (i.e., petites fibres) et de fibres somatiques afférentes et efférentes (i.e., grandes fibres). Elles possèdent le seuil de recrutement le plus bas (0.02 à 0.2 mA) et sont par conséquent activées en premier avec une vitesse de conduction de 5–120 m/s. Les fibres de type B sont des fibres préganglionnaires afférentes et efférentes, également myélinisées et de diamètre intermédiaire 3 µm. Elles sont recrutées par suite de stimulations dont l'intensité varie entre 0.04 à 0.6 mA. Leur vélocité de conduction varie entre 3 et 15 m/s. Enfin, les fibres de type C recouvrent environ 70% de toutes les fibres vagales. Ce sont les plus petites avec un diamètre variant de 0.2 à 1.5 µm et sont non myélinisées. Elles possèdent le seuil de recrutement le plus élevé (> 2 mA) et transmettent des informations viscérales provenant du vaste ensemble d'organes viscéraux. Leur vélocité de conduction est estimée à 2 m/s. Une étude de Krahl et al. (2001) a mis en évidence qu'une lésion des fibres de type C n'empêchait pas la VNS de supprimer les convulsions induites par le pentylènetétrazol chez le rat. Cette étude suggère que seules les fibres de type A et B sont impliquées dans le mécanisme d'action de la VNS. Également, l'intensité de stimulation généralement utilisée se situe en-dessous du seuil d'activation des fibres de type C. En conséquence, le VN constitue un avantage adaptatif pour faire face au stress (branche vagale ventrale). En situation de danger, le retrait rapide de l'activité vagale permet une accélération en moins d'une seconde du rythme cardiaque permettant l'amorcement d'une réaction adaptée. Cette évolution neuroanatomique et fonctionnelle de l'ANS offre un substrat aux réactions cognitives, émotionnelles et physiologiques pour rendre compte des réponses comportementales complexes des individus. Le VN pourrait donc constituer une contre-mesure prometteuse afin de promouvoir des réponses adaptatives.

3.3. La stimulation vagale invasive

L'application la plus fréquente de la stimulation du nerf vague invasive (*invasive vagus nerve stimulation*, iVNS) nécessite l'implantation chirurgicale d'une électrode bipolaire hélicoïdale à bobine placée autour du VN gauche dans le cou, reliée à un générateur d'impulsions implanté par voie sous-cutanée infraclaviculaire dans la poitrine. Cette technique fut mise au point par Jake Zabara dans les années 1980, car elle s'est avérée recouvrir des effets antiépileptiques prometteurs chez des modèles canins (Zabara, 1985 ; Zabara, 1992).

L'iVNS est devenue l'une des premières formes de neuromodulation chez l'être humain (Yuan & Silberstein, 2016c). Elle est idéale pour les pharmacorésistants, notamment chez les patients atteints d'épilepsie réfractaire ou de dépression (Austelle et al., 2021 ; Tanganelli, 2022). Cependant, l'iVNS nécessite une intervention chirurgicale coûteuse et invasive. Bien que cette procédure puisse améliorer la santé de nombreux patients, de nombreux effets secondaires sont présents (e.g., risques liés à la chirurgie, bradyarythmie, hématome péritrachéal, infections, asystolie, dyspnée, dysfonction des cordes vocales, modification des patterns respiratoires) (Fitzgerald, 2013 ; Iriarte et al., 2009 ; Marzec et al., 2003 ; Fahy, 2010 ; Ventureyra, 2000).

L'iVNS fut une réelle révolution dans le traitement de l'épilepsie réfractaire aux traitements médicamenteux (1994 en Europe, 1997 en Amérique du Nord), et dans le cadre de la dépression chronique résistante au traitement (2005). Elle est effectivement idéale pour les pharmacorésistants aux crises d'épilepsies (Tanganelli et al., 2002 ; Usami et al., 2013) et a ainsi pu améliorer la vie de nombreux patients. Toutefois, ces dernières années ont vu l'arrivée de méthodes moins invasives développées comme alternatives moins coûteuses, plus conviviales pour le patient et pouvant être déployées rapidement. Parmi ces dernières figure taVNS.

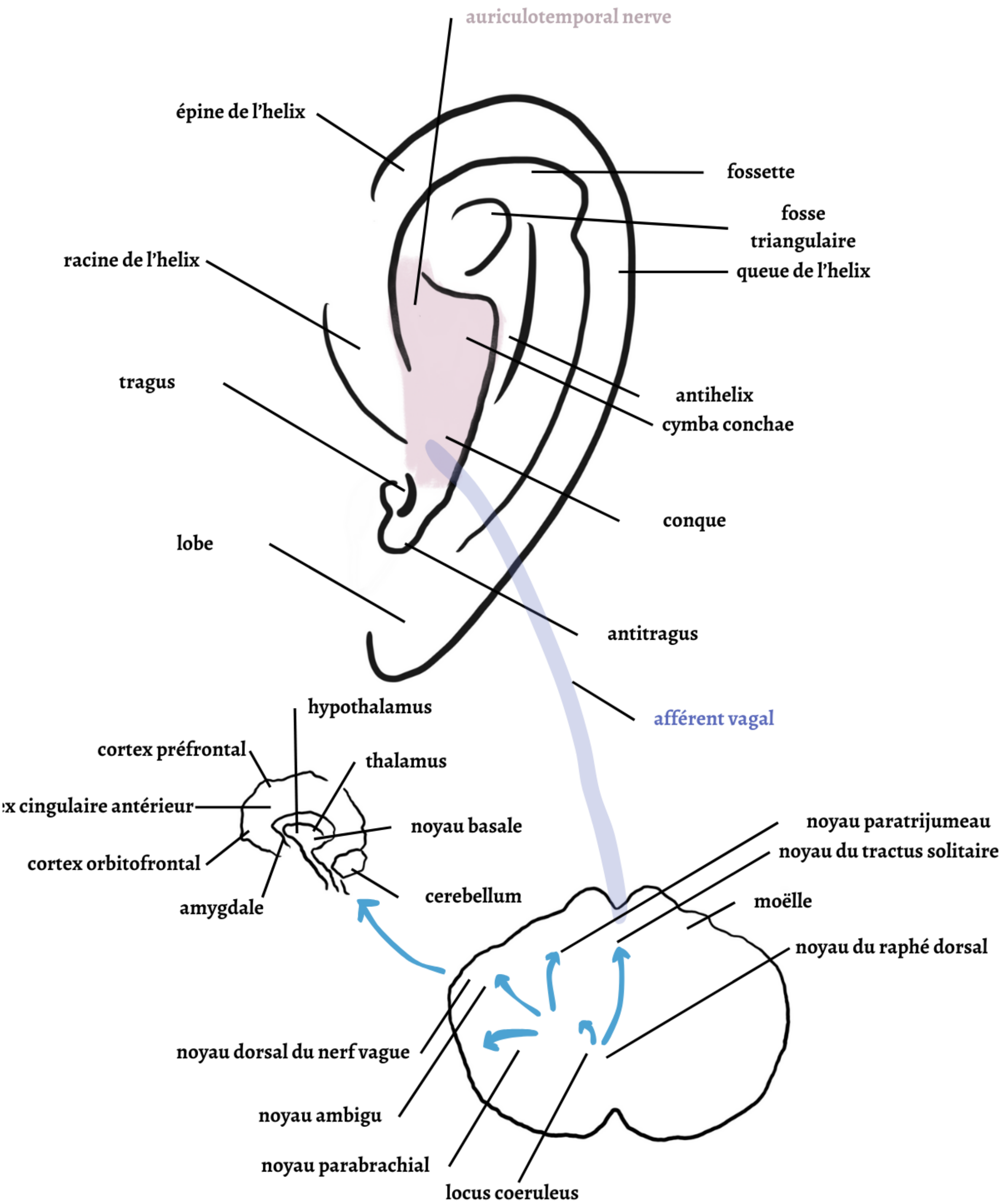
3.4. La stimulation vagale non invasive

La taVNS est une méthode relativement nouvelle de stimulation neurale non invasive introduite comme une alternative à la procédure iVNS. Elle ne nécessite aucune intervention chirurgicale en ciblant le champ récepteur cutané de l'ABVN au niveau de l'oreille externe. Également appelée nerf d'Arnold, l'ABVN est un des trois nerfs sensoriels qui fournit une innervation somatosensorielle à l'oreille externe (Butt et al., 2019). L'ABVN est également considérée comme la voie afférente d'autres réflexes somatoviscéraux dont le phénomène gastro-auriculaire, le phénomène pulmono-auriculaire, le réflexe auriculo-génital et le réflexe auriculo-utérin (Engel, 1979 ; Gupta et al. 1986). Ce dernier prend naissance dans le ganglion supérieur du VN à l'intérieur du foramen jugulaire, traverse transversalement le canal facial, pénètre dans le canal de l'os pétreux et émerge de la fissure tympanomastoïdienne, pour innerver le méat acoustique externe et le pavillon (Butt et al., 2019). Plus particulièrement, deux zones auriculaires cutanées ont été reconnues comme ciblant l'ABVN lors de sa stimulation, à savoir la cymba conchae et le tragus (Badran et al., 2018a ; Borges et al., 2021 ; Yakunina et al., 2017) (Figure 13). Kaniusas et ses collègues (2019) ont mis en évidence d'autres régions partiellement mais non exclusivement innervées par le VN dont l'anthélix (73%), la cavité de la conque (45%), le tragus (45%), la crus de l'hélix (20%) et la crura de l'anthélix (9%). L'étude de Peuker et Filler (2002) est la première étude anatomique à avoir mis en évidence sur 14 oreilles humaines, le trajet complet de l'alimentation nerveuse et chaque branche auriculaire en identifiant son origine. Selon les résultats obtenus, le tragus est innervé à 45% par l'ABVN tandis que la cymba conchae a 100% de ses fibres en provenance de l'ABVN. Selon une autre étude visant à cartographier la localisation précise des nerfs situés dans le pavillon de l'oreille et le segment cartilagineux du canal auditif (i.e., méat acoustique externe cartilagineux), la densité relative des nerfs dans le méat acoustique externe cartilagineux est plus élevée que dans les cavités conchoïdes ainsi que dans les parois supérieure et postérieure du méat acoustique externe cartilagineux que dans la paroi antérieure (Bermejo et al., 2017). Aussi, la densité des nerfs et des fibres nerveuses myélinisées était plus élevée en dehors du cartilage et dans le canal auditif et les nerfs plus nombreux dans les segments supérieur et postérieur-inférieur que dans les segments antérieur-inférieur du canal auditif (Bermejo et al., 2017).

Le signal électrique qui part de l'ABVN atteint le NTS (i.e., reçoit environ 95% des projections du VN), une structure cruciale qui se projette vers diverses zones du cerveau, notamment des régions corticales telles que le cortex cingulaire antérieur et le cortex préfrontal (e.g., cerveau antérieur, du limbe et du tronc cérébral, notamment le noyau trigéminal spinal, l'aire parabrachiale, le raphé dorsal, le gris périaqueducal, le thalamus, l'amygdale, l'insula, le noyau accumbens, le noyau de la stria terminalis et l'hypothalamus). Comme l'ont montré plusieurs études d'imagerie par fMRI, la taVNS induit, contrairement à la stimulation de contrôle « *sham* », une activité plus élevée dans le NTS, dans le PFC gauche et dans les aires cingulaires (Badran et al., 2018a ; Frangos et al., 2015 ; Kraus et al., 2013 ; Yakunina & Kim, 2017). Le NTS se projette dans le locus coeruleus, principale structure cérébrale noradrénergique, qui semblerait être le médiateur de plusieurs des effets sous-jacents à la VNS. La fMRI a mis en évidence le rôle clé présumé de ces deux structures lors de la taVNS (Figure 13 et 14).

Figure 13

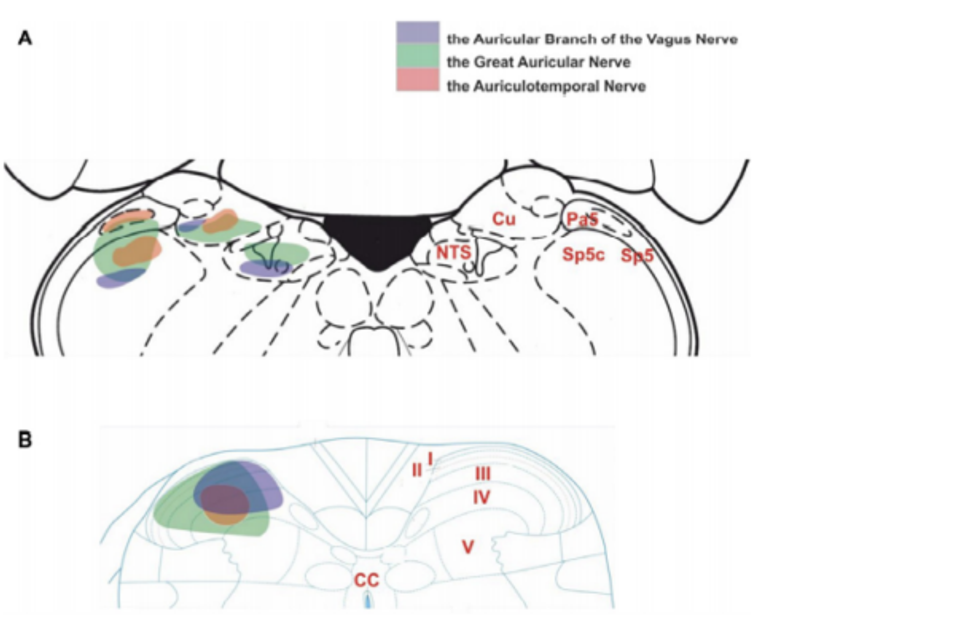
Stimulation auriculaire et principales projections dans le cortex



L'ABVN serait composé de fibres Aβ myélinisées (i.e., fibres d'un diamètre de 7 à 10 µm) représentant environ 20% du total des axones myélinisés, de fibres Aδ myélinisées (i.e., fibres d'un diamètre de 2 à 5 µm) représentent environ 50% du total des axones myélinisés et de fibres C non myélinisées. D'un point de vue théorique, il semble raisonnable que les intensités de stimulation du taVNS ne soient pas inférieures à 0.75 mA pour recruter les fibres de type A de l'ABVN. En effet, la stimulation de l'ABVN activerait les fibres myélinisées épaisses (i.e., inactivation des fibres de type C).

Figure 14

Diagramme schématique des projections afférentes de l'oreille externe vers le tronc cérébral et la moelle épinière cervicale supérieure (Butt et al., 2019)



i.e., noyau du tractus solitaire, NTS ; noyau cunéiforme, Cu ; noyau paratrigéminal, Pa5 ; voie spinale trigéminale, Sp5 ; noyau trigéminal caudal, Sp5c.

Les paramètres de stimulation de la taVNS peuvent varier en termes d'intensité du courant (i.e., intensité du stimulus électrique, mesurée en milliampères, mA), de largeur d'impulsion (i.e., durée de l'impulsion électrique, mesurée en microsecondes, µs), de fréquence (i.e., mesurée en Hertz, Hz), de rapport cyclique (i.e., temps d'activation et de désactivation du stimulus, mesuré en secondes, s) et de durée de la séance (i.e., mesurée en minutes, min) (Badran et al., 2019). La fréquence la plus couramment appliquée dans les études humaines est actuellement de 25 Hz. Cependant, de plus en plus d'études utilisent des systèmes fabriqués en interne afin de pouvoir générer plusieurs intervalles de stimulation (Badran et al., 2018a ; Badran et al., 2018b ; Liu et al., 2016 ; Machetanz et al., 2021a ; Machetanz et al., 2021b ; Mouli et al., 2021 ; Yakunina et al., 2017). Par ailleurs, depuis de nombreuses années se pose la question de la latéralité de la stimulation. Historiquement, la stimulation taVNS est pratiquée à gauche afin d'éviter de potentiels effets secondaires tel que mentionné précédemment. Toutefois, la littérature n'a pas mis en évidence de contre-indication relative à la latéralité de la stimulation dans le cadre de la taVNS (Farmer et al., 2020).

Le dispositif taVNS commercialisé le plus répandu (tVNS® Technologies GmbH, Erlangen, Germany) délivre le courant sous forme d'impulsions carrées rythmiques (Yuan & Silberstein, 2016b). Le dispositif NEMOS puis tVNS® a reçu la certification européenne (certification CE, qui indique la conformité juridique et la sécurité, mais pas nécessairement l'efficacité clinique) en tant que traitement de l'épilepsie et de la dépression en 2010, de la douleur chronique en 2012 et de l'anxiété en 2019. Les paramètres du système sont les suivants : 200 et 300 µs à 25 Hz, et un cycle de 30s on, 30s off. Il s'agit d'un dispositif relativement bien toléré chez les individus sur lequel il a été utilisé. Afin d'activer les fibres afférentes myélinisées du VN, l'intensité du stimulus est ajustée à un niveau compris entre le seuil de détection (première sensation perceptible ou picotement) et le seuil de douleur (première sensation de piqûre ou désagréable) (Ellrich et al., 2019). Dans la mesure où la sensation de picotement est similaire à la sensation tactile, Ellrich et al. (2019) ont suggéré que la stimulation non douloureuse des nerfs périphériques active préférentiellement les fibres Aβ mais pas les fibres Aδ. Les fibres réellement stimulées dépendent des paramètres de stimulation.

Un ensemble de paramètres de stimulation doit être pris en compte lorsqu'il s'agit d'utiliser le tVNS dans le cadre de la recherche et de la clinique. Les paramètres de stimulation du tVNS peuvent varier en termes d'intensité du courant (mA), de largeur d'impulsion (µs), de fréquence (Hz), de rapport cyclique (s) et de durée de la séance (min) (Badran et al., 2019). En outre, les effets secondaires de la stimulation, le type de stimulation fictive ou de contrôle et l'emplacement de la stimulation et des électrodes fictives peuvent influencer les résultats de la tVNS. L'impact de chacun de ces paramètres de stimulation sur la psychophysiologie et sur les résultats cliniques est incomplètement compris. Malgré le nombre croissant d'études, il n'existe pas de consensus clair concernant les paramètres optimaux à adopter pour la recherche sur la taVNS. De plus, il n'y a pas de consensus clair concernant les éléments de rapport standard minimaux dans la littérature sur la taVNS.

3.5. Le potentiel scientifique de la stimulation transcutanée auriculaire

Ces dernières années, la littérature a pu montrer son potentiel dans nombre de domaines. En effet, la taVNS a montré son efficacité dans la réduction des symptômes ou dans une meilleure récupération de patients atteints d'anxiété, de retard psychomoteur, d'épilepsie, de diabète, d'intolérance au glucose, de douleurs chroniques, de céphalées, d'accidents vasculaires cérébraux, de réadaptation post accident vasculaire cérébral, de peur, de troubles cognitifs, de fibrillation auriculaire, d'infarctus du myocarde, d'insuffisance cardiaque, d'arythmie, de tachycardie, d'acouphènes, de syndrome de Prader-Willi, de schizophrénie, de syndrome de stress post-traumatique, de maladie de Parkinson, de troubles de la conscience, de déclin cognitif, de lésions cérébrales, de douleurs chroniques, d'obésité, de dysfonctionnements gastro-intestinaux, d'occlusions intestinales postopératoires, de maladies inflammatoires de l'intestin, du cancer du côlon et de dystonie (Austelle et al., 2021 ; Burger et al., 2019 ; Kong et al., 2018 ; Straube et al., 2015 ; Redgrave et al., 2018 ; Ridgewell et al., 2019 ; Wang et al., 2022). La taVNS aurait particulièrement des bénéfices importants chez les patients épileptiques pharmacorésistants au traitement de première ligne (Bauer et al., 2016 ; Stefan et al., 2012). Elle permet une réduction efficace de la fréquence des crises. Une étude pilote a établi pour la première fois l'effet antidépresseur du taVNS en 1996 (Hein et al., 1996). Depuis, des preuves convaincantes ont été fournies quant à un effet antidépresseur de la taVNS (Rong et al., 2016 ; Wang et al., 2022 ; Wu et al., 2018). Ellle permettrait notament de réduire de manière significative des symptômes tels que l'anxiété, le retard psychomoteur, les troubles du sommeil et le désespoir (Wang et al. 2022). Cet effet serait médié par le réseau par défaut du NTS et lobe limbique (Fang et al., 2016).

Des études empiriques ont montré que la stimulation vagale l'influence l'ANS. Ainsi, elle peut affecter le système cardiovasculaire (De Ferrari et al., 2011 ; Jiang et al., 2020 ; Olshansky et al. 2008). Paleczny et al. (2021) ont mis en évidence que la taVNS exerçait des effets cardioinhibiteurs clairs chez les sujets neurotypiques ayant une fréquence cardiaque élevée. Stavrakis et al. (2020) ont montré que la taVNS diminuait la fibrillation auriculaire.

Également, la taVNS améliore différentes fonctions psychométriques, notamment le bien-être, la vigilance et les performances cognitives, conjointement à une diminution de l'humeur négative (Kaniusas et al., 2019) mais également l'apprentissage (D'Agostini et al., 2021). Steenbergen et al. (2020) ont suggéré que l'état d'humeur positive pourrait être un proxy de l'éveil pertinent pour la tâche, influençant probablement l'efficacité de la stimulation vagale afférente sur les processus d'autocontrôle. Récemment, plusieurs études ont aussi mis en avant son bénéfice dans le traitement de la Covid-19 (Ferrer et al., 2020 ; Dedoncker et al., 2021 ; Kaniusas et al., 2020). Plus spécifiquement, la taVNS améliorerait la qualité du sommeil, notamment chez les individus souffrants d'insomnie (Jiao et al., 2020 ; Luo et al., 2017 ; Yoon, 2019 ; Zhao et al., 2020). Une étude récente suggère également une relation causale entre le flow, et la taVNS via le système noradrénergique (i.e., activation du locus ceoruleus et augmentation de la norépinéphrine) (Colzato et al., 2018).

Ces dernières années, les études se sont multipliées pour mettre en exergue que la VNS activerait des zones clés du réseau intéroceptif (Critchley & Harrison, 2013 ; Ferstl et al., 2021 ; Paciorek et al., 2020 ; Quadt et al., 2019 ; Richter et al., 2021). Le rôle de la taVNS sur les dimensions psychologiques de l'intéroception a été mis en évidence par Villani et al. (2019). Ces derniers ont montré que la taVNS améliorait la capacité des participants à identifier sans erreur leurs battements cardiaques. Ils avaient une confiance plus importante dans leurs décisions, mais cela n'a pas affecté leur conscience intéroceptive. Également, une étude a montré que la taVNS modulait les signaux de rétroaction intéroceptifs en améliorant l'humeur après un effort (Ferstl et al., 2021). Il est sans nul doute que l'intégration de signaux corporels de qualité renseignant sur l'état interne de l'organisme afin d'assurer sa survie semble être nécessaire pour un traitement cognitif et émotionnel adaptatif (Barrett & Simmons, 2015 ; Critchley & Harrison, 2013 ; Critchley & Garfinkel, 2018 ; Seth, 2013 ; Seth & Tsakiris, 2018). L'ANS interprète et porte un regard sur notre monde en concomitance avec les informations qu'il reçoit de l'environnement. L'un et l'autre se nourrissent mutuellement. Le fait que la VNS soit directement en lien avec des processus cérébraux de haut niveau justifie l'implication et l'imbrication de ces systèmes dans le processus adaptatif.

Les effets secondaires de la stimulation, le type de stimulation fictive ou de contrôle et l'emplacement de la stimulation et des électrodes fictives peuvent influencer les résultats de la taVNS. L'effet secondaire le plus courant est l'irritation de la peau au niveau du site de stimulation. Parmi les autres effets secondaires survenant dans plus de 1% des cas, on peut citer : rhinopharyngite, céphalées, vertiges, nausées/vomissements, affaissement du visage, douleurs cervicales, démangeaisons, changements thymiques (Jacobs et al., 2015 ; Goadsby et al., 2014 ; Redgrave et al., 2018). Les effets indésirables graves sont rares et aucun n'a été confirmé comme résultant de la taVNS (Redgrave et al., 2018).

Cependant, il est à mentionner que l'ensemble des études mettent en évidence de nombreuses lacunes, hétérogénéités au sein des recherches mais également une absence de consensus sur les paramètres de stimulation optimaux et la fréquence des interventions. De plus, il n'y a pas de consensus clair concernant les éléments de rapport standard minimaux dans la littérature sur la taVNS. Nombre sont aussi ceux qui ne mettent en évidence aucun effet de la taVNS sur la cible en question (Burger et al., 2018 ; Genheimer et al., 2017 ; Wolf et al., 2021). C'est dans ce cadre que l'article de Farmer et al. (2020) a été publié avec la volonté d'apporter des recommandations en vue des études futures. De plus en plus de revues soulignent la nécessité d'utiliser des biomarqueurs afin de renforcer l'efficacité de la taVNS mais également la méthodologie de l'étude en elle-même (Badran et al., 2019 ; Redgrave et al., 2018 ; Thompson et al., 2021 ; Usichenko et al., 2022 ; Wang et al., 2021 ; Yap et al., 2020).

L'avènement des modèles d'apprentissage automatique ces dernières années constitue également une approche prometteuse afin de mieux détecter, identifier, prévenir les pathologies et les individus à risque de dégrader leur état de santé.

Le devenir d'une technologie de prédiction de pointe ou comment l'intelligence artificielle a pour vocation de servir la médecine de demain

L'AI est en passe de devenir une des plus grandes révolutions du XXI^{ème} siècle. Elle a l'ambition de simuler l'intelligence humaine via des programmes informatiques capables de comprendre le fonctionnement du comportement humain (Signorelli, 2018). Plus que cela, l'AI est capable de s'affranchir des lignes de codes en évoluant en toute autonomie sans qu'aucun programme ne soit à l'origine de son évolution. En conséquence, cette technologie promet d'avoir un impact majeur sur l'humanité. Depuis quelques années, elle est entrée dans une nouvelle ère qui s'insuffle dans tous les domaines de la société (e.g., banque, logement, tourisme, santé). En effet, ses applications se multiplient face à l'essor du Big Data, et de l'augmentation des capacités de calcul.

Toutefois, un des défis réside dans son implication dans les enjeux de prévention de la pathologie et de la promotion de la santé, mais également pour en tirer le meilleur parti et une utilisation adéquate. En effet, l'AI vient en complémentarité des activités humaines déjà bien établies. Son développement nécessite de repenser nos manières de réfléchir mais en aucun cas, il s'agit de s'aliéner à une quelconque technologie. L'AI n'est pas une fin en soi mais le début d'un nouveau partenariat entre une entité humaine et non matérielle. Que ce soit au niveau individuel ou collectif, la place de l'AI est à creuser avec une complémentarité qui nous permet de propulser l'état d'avancement des recherches actuelles en matière d'innovation. Le rapport Villani (2018) met en exergue à cet égard trois piliers fondateurs autour du développement de l'AI en France : (1) développer des usages et des applications permettant de faire évoluer l'économie et le bien commun français, notamment en matière de e-santé ; (2) mettre en place des plateformes sectorielles de mutualisation permettant de fournir les moyens matériels à son développement ; (3) soutenir l'innovation en diminuant les contraintes réglementaires.

Elle est en passe de révolutionner l'ensemble du quotidien en apportant des évolutions majeures à la société, notamment dans le domaine de la santé (Hamet & Tremblay, 2017 ; Buch et al., 2018 ; Briganti & Le Moine, 2020), devenu l'un des quatre secteurs stratégiques de la politique française en matière d'AI (Villani, 2018). Un de ses bénéfices à combattre les maladies est son emploi dans le cadre de la pandémie du COVID-19. En effet, l'AI a fortement progressé permettant de détecter à distance les individus présentant des symptômes du SARS-CoV-2, de rendre les soins plus inclusifs, diffus mais surtout personnalisés à tout un chacun réduisant ainsi considérablement le temps alloué au diagnostic, l'exploitation des résultats mais aussi la récupération des patients (Barbieri et al., 2021 ; Zhao et al., 2022). Un des enjeux de l'AI en matière de santé est de croiser des quantités importantes de données pour mettre en évidence des corrélations et permettre l'identification de facteurs de prédiction. Récemment, Lin et al. (2021) ont mis en évidence l'utilité de l'AI pour la surveillance de la fréquence cardiaque et de la pression artérielle dans la gestion du stress. La richesse de ses applications n'est pas à démontrer. Dans une étude préliminaire non publiée, nous avons pu explorer l'efficacité de cet outil pour prédire la vulnérabilité au décours d'une patrouille sur un sous-marin nucléaire lanceur d'engins (*sub-surface ballistic nuclear-powered missile submarines*, SSBN). Un vecteur à support de machine (*support vector machine*, SVM) a pu prédire, en utilisant la HRV en ligne de base des sous-mariniers à 83%, la vulnérabilité à la fatigue et au stress à la fin de la patrouille.

L'avènement de l'AI peut être un vecteur permettant d'offrir la possibilité de mieux comprendre et prédire les individus les plus à risque de se dégrader au cours d'une mission dans ces environnements hors du commun. Depuis novembre 2022, nous avons pu mesurer son ampleur avec la sortie de Chat GPT 3.5 par OpenAI qui transforme déjà les méthodes de travail. L'AI est initiatrice d'une médecine où le monitoring en temps réel alimente la base de données de l'algorithme. Un ensemble de capteurs, toujours plus performants et intégrés à l'individu, permettent de retranscrire avec le plus de précision possible l'environnement écologique dans lequel il se trouve. L'exploitation de ces informations permettent de retracer une image précise d'un état de santé au cours du temps (i.e., psychologique, physiologique, sensitif, cognitif), de faire évoluer les prédictions et ainsi la prise en charge éventuelle via des contremesures. Cependant, par rapport à d'autres domaines de la santé, les données disponibles dans les environnements ICE/EUE sont beaucoup plus petites et hétérogènes, affectant sans aucun doute la construction des modèles de l'AI. Se pose dans ce contexte la question de l'apprentissage d'un jeu de données. Initialement, l'algorithme sépare un jeu de données entre : (1) un jeu d'apprentissage permettant à celui-ci de s'entraîner à catégoriser et (2) un jeu de validation aveugle à l'apprentissage permettant de vérifier la robustesse du modèle. La quantité de données allouée, leur qualité ainsi que leur annotation représentent des facteurs déterminant dans la précision du modèle. Un travail avancé en amont sur la recherche des données ayant un poids important dans la prédiction est un élément clé. Plusieurs techniques sont utilisées afin de dépasser les limites du jeu de données : (1) l'augmentation des données existantes en ajoutant des données supplémentaires aux données disponibles (Andonie, 2010 ; Lateh et al., 2016) ; (2) l'utilisation d'un panel de sélection pour choisir le meilleur modèle de prévision parmi plusieurs modèles (i.e., l'algorithme présentant l'erreur la plus faible est sélectionné et les autres candidats rejetés) (Shaikhina & Khovanova, 2017) ; et (3) le réglage fin des paramètres d'un modèle de prévision individuel pour obtenir la meilleure précision possible (Slifker & Shapiro, 1980). Les algorithmes de *machine learning* (i.e., apprentissage machine), combinés à des méthodes spécifiques à un set d'échantillon de données limités ouvrent la voie vers un juste équilibre entre l'enjeu de prédiction et la validation du modèle. De nouvelles approches d'analyse de données permettent également une analyse non plus entre l'interaction dynamique dans le temps des facteurs mais sur leurs relations concurrentes (Driver & Voelkle, 2018 ; Hamaker et al., 2018).

Un enjeu clé est de trouver le juste rapport entre la qualité du modèle et la fin qu'il dessert. *In fine*, il est primordial que ce travail soit respectueux d'une éthique de l'AI dans laquelle l'individu a intégralement sa place et un rôle à jouer.

Ainsi, elle semble être un outil prometteur permettant de prédire les profils d'individu à risque de mal-adaptation en vue des missions spatiales de demain. Avoir le potentiel de détecter avant le départ ceux qui sont à risque de se dégrader est un enjeu majeur à la fois de sélection des futurs équipages, mais également de ciblage une fois sur place avec la mise en œuvre de solutions efficaces (e.g., amorcer un entrainement spécifique à la suite d'une diminution de la performance). Apporter une solution clé en main s'avère nécessaire mais il est primordial que celle-ci soit adaptée à chacun des individus. C'est également soulever la question du risque et de la transparence. En effet, il n'en reste pas moins qu'un des enjeux majeurs des futurs équipages spatiaux sera de réduire à son maximum le risque d'échec de la mission. Celui-ci passe par une surveillance accrue et une détection fiable de l'état de santé de chacun des membres de l'équipage, que ce soit son état psychologique, cognitif ou sensorimoteur. Une solution personnalisée que l'AI est à même de fournir et qui sera améliorée avec les années à venir.

Les concepts ayant été définis au cours de cette introduction, nous allons pouvoir amorcer le début du voyage par la revue de question portant sur l'impact de l'espace et de environnements analogues sur les réponses adaptatives de l'espèce humaine. Du voyage des environnements les plus dangereux pour l'être humain en passant par la profondeur des océans aux confins noirs de l'espace, nous allons explorer l'adaptation à travers les modulations de l'ANS et de l'intéroception en nous immergent dans l'un des plus grands nerfs du corps, le vague et le code binaire des machines.

Problématique

Une profonde responsabilité professionnelle et éthique revient à ceux en charge de l'évaluation du risque pour la vie humaine qui accompagnera les LDSE. Le risque encouru sera grand, personne ne peut le quantifier à cet instant. Ce risque doit aussi être appréhendé au plus juste au regard des conséquences pour la vie humaine, même si ce sera, *in fine*, une prise de décision personnelle de l'astronaute, qui, en toute connaissance de cause, acceptera le risque d'un voyage vers une contrée lointaine. Cette réalité du risque nourrit nombre d'études mécanistiques et cliniques visant à identifier des mécanismes d'adaptation pour valider des contremesures efficientes. Ces recherches sont fondamentales pour le succès de la mission et la santé de ces professionnels d'exception, futurs « explorateurs » de l'Univers.

Certaines questions posées relatives au maintien de la vie restent les mêmes que celles posées au début de la conquête spatiale, et les réponses toujours insuffisantes. L'espèce humaine est-elle capable d'adaptation dans ces milieux hors du commun ? Les défis posés par le maintien de la vie dans les conditions les plus extrêmes sont toujours présents même si les conditions de vie ont considérablement évolué dans ces environnements. Ils engendrent des réactions physiologiques et psychologiques, modifient les structures cérébrales, altèrent les fonctions cognitives dites de haut niveau ou processus cognitifs complexes, le système vestibulaire et sensoriel de l'organisme et challengent la récupération, qui est *in fine* souvent invisible des études longitudinales. Ces signes à bas bruits, ensemble de signaux faibles, constituent un risque de plus haut niveau en ce qu'ils soulignent une dérive fonctionnelle qui sera susceptible de compromettre la réponse de l'astronaute aux challenges qu'il va rencontrer, et l'aboutissement de la mission (Garrett-Bakelman et al., 2021). D'autres questions se posent. Citons notamment la question du facteur temporel qui pose comme enjeu le maintien dans la durée de la question de l'adaptation *per se* dans ces milieux, associé au pattern d'évolution des changements cités précédemment. Notons également que la littérature reste bien souvent silencieuse sur le rôle des perceptions sensorielles impliquées dans ces changements, alors même qu'un environnement sensoriel non écologique peut être rapproché d'un appauvrissement sensoriel dont on connait les effets négatifs chez l'enfant et la personne âgée. Enfin, se pose la question de la pertinence de l’environnement ciblé pour l’étude de l’adaptation. Les environnements analogues présentent des caractéristiques d’isolement, de confinement, voire d’extrême et d’inhabituel (i.e., ICE/EUE). Ils constituent de ce fait des environnements d’intérêt et disponibles pour conduire des expérimentations d’évaluation et de validation de contre-mesures.

Au regard de ces besoins en recherche, force est de constater que de nombreux défis majeurs persistent encore pour le succès des missions de demain vers d’autres planètes. Ainsi, de nombreux points restent en suspens :

1. Les données disponibles sur les vols spatiaux sont insuffisantes pour permettre une évaluation objective et une prédiction efficiente et réelle des problèmes de santé comportementale susceptibles de se poser lors des prochains voyages de demain.

2. Les environnements ICE/EUE offrent une richesse de savoir dont il faut se saisir. Néanmoins, leurs nombreuses différences limitent la généralisation des résultats.

3. Il est nécessaire d'obtenir davantage d'informations sur les systèmes de soutien à l'interface entre les groupes basés au sol et ceux vivant dans l’espace.

4. En l'absence d'une analyse valide et fiable de la base de données existante, il n'est pas possible de déterminer avec précision dans quelle mesure l’espèce humaine est capable d’adaptation dans les environnements ICE/EUE.

5. La multiplicité des méthodologies de recherche et des variables impliquées conduit à un tableau mixte de résultats limitant leur généralisation et engendrant des limites qu’il est difficile de surmonter à l’heure actuelle.

6. Bien que les données provenant d'environnements naturels analogues puissent être utiles, y compris les études de simulation, il reste nécessaire d'accumuler des connaissances basées sur des observations provenant de recherches systématiques dans des environnements terrestres extrêmes naturels (e.g., base de recherche en Antarctique, sous-marin nucléaire) et

simulés (i.e., modules HERA, NEEMO, Lunar Palace) et dans des lieux comme l'ISS.

7. Les facteurs qui influencent sérieusement la santé comportementale et l'efficacité des performances des individus au cours des LDSE restent à mieux planifier. Ces derniers ne se limitent pas à une évaluation biologique mais bien à des interactions multimodales qui interviennent entre les différents acteurs de l'organisme. Une vision holistique de l'adaptation est un réel besoin dès lors que les missions s'inscriront dans la durée.

Objectifs et retombées

Au regard de ces besoins dont la liste n'est pas exhaustive, ce travail de Thèse a deux objectifs expérimentaux principaux :

1. Évaluer l'impact des environnements analogues à l'espace en ICE/EUE sur les professionnels afin de mieux appréhender l'adaptation psychologique, cognitive, physiologique, sensorielle et comportementale aux contraintes environnementales.
2. Caractériser des profils d'adaptation et proposer des contre-mesures aux plus vulnérables au moyen des dernières avancées médicales et technologiques pour maintenir des conditions opérationnelles optimales et assurer la santé des membres de l'équipage.

Afin d'apporter une réponse éclairée à ces deux objectifs principaux de recherche, nous allons décoller pour expérimenter des accélérations nous conduisant de la microgravité à l'hypergravité, naviguer autour de contraintes environnementales majeures (i.e., isolement, confinement, survie, extrême), faire face à des situations de dangers extrêmes, plonger au plus profond des océans, pour nous rendre à notre dernière destination, sur les terres de glaces dans une des contrée la plus reculée de la Terre. Chemin faisant, nous devrons mobiliser d'importantes ressources pour maintenir les réponses psychologiques, cognitives, physiologiques, sensorielles et *in fine*, comportementales à un état stable. Ce périple, nous conduira à expérimenter les limites du monde visible et à stimuler pour réguler nos messages intero-exteroceptifs.

Ainsi, la portée de ce travail s'inscrit dans trois intérêts spécifiques :

a. <u>Intérêt expérimental</u> : l'ensemble des paradigmes sélectionnés constitue une batterie psycho-physio-cognitivo-sensorielle opérationnelle pour explorer la qualité du fonctionnement d'un individu stressé en milieu extrême et qui peut être utilisée avec d'autres populations et environnements.
b. <u>Intérêt théorique</u> : caractériser les perceptions sensorielles comme cause ou conséquence du stress adaptatif. La validation d'un lien entre les modèles de changement de la perception sensorielle et les modèles de stress adaptatif

ouvrirait une discussion sur les causes/conséquences des changements psychologiques observées au sein des environnements ICE/EUE. Ces résultats permettront au-delà des préconisations pour s'adapter aux situations de confinement en lien avec une pandémie.

c. Intérêt opérationnel : valider des dispositifs pertinents pour réduire le stress chez les individus en mission dans des environnements ICE/EUE. Leur valorisation est à prévoir dans le quotidien des environnements professionnels appauvris comme des LDSE. Dans ce cadre, la VR couplée à l'activité physique, et la taVNS constitueraient des contre-mesure modernes utilisant des techniques nouvelles générations à nourrir avec des données de terrain.

Annonce de plan

Plongé dans la peau d'un équipage en mission LDSE et en route vers une contrée incertaine, les concepts théoriques ont été présentés afin d'éclairer les mécanismes abordés au sein des différentes recherches. Notre voyage hors du temps peut ainsi réellement débuter.

Le premier chapitre posera le contexte de la Thèse en retraçant l'état de l'art et en présentant la revue de littérature PRISMA.

Le deuxième répondra au premier objectif expérimental de la Thèse qui porte sur l'impact des environnements analogues à l'espace en ICE et en environnement extrême et inhabituel EUE sur les professionnels.

Le troisième chapitre répondra au deuxième objectif expérimental de la Thèse à savoir caractériser des profils d'adaptation et proposer des contre-mesures aux sujets les plus à risque de mal-adaptation.

CHAPITRE I

Au-delà des frontières : En route vers les missions spatiales de demain

Être le premier à entrer dans le cosmos,
à se lancer seul dans un duel
sans précédent avec la nature ;
que pourrait-on rêver de plus ?

Yuri Gagarin

La séparation prolongée avec les êtres chers, la promiscuité, les températures extrêmes, le manque d'oxygène, les concentrations élevées de CO2, la lumière artificielle, les radiations, la pesanteur, l'isolement et le confinement, la monotonie sensorielle pour ne citer que les majeurs sont autant de facteurs mettant les capacités d'adaptation des équipages de ces milieux d'exception à rude épreuve, même les plus entraînés.

Nous allons ainsi parcourir et retracer l'ensemble des impacts pathogéniques et salutogéniques d'un séjour dans les extrêmes sur les réponses psychiatriques, psychologiques, neurophysiologiques, physiologiques, cognitives et sensorielles pour ne citer que les plus connus que la littérature a étudiés. Ces effets dans les environnements isolés et confinés (*isolated and confined*, ICE) ; extrêmes et inhabituels (*extremes and unusuals*, EUE) furent recensés depuis bien des années, avant même le premier vol spatial. Il s'avère important de faire un premier état des lieux de la littérature avant les années 2005 avant de présenter une revue de littérature de ces impacts sur l'adaptation humaine étudiés depuis cette date. Comme nous le verrons, si les études conduites avant 2005 sont enrichies par le travail de ces dernières années, force est de constater que de nombreuses questions restent en suspens. La date de 2005 fut choisie arbitrairement pour donner suite au constat d'un ralentissement des publications passée cette date. En conséquence, afin de mieux appréhender les résultats publiés ces dernières années, les études sélectionnées à partir de 2005 nous semblaient être plus représentatives.

A la frontière entre la vie, la survie et l'extinction : les âmes des extrêmes

La littérature fait état de symptômes psychiatriques d'anxiété et de dépression chez les individus se trouvant dans ces environnements uniques (Palinkas, 1995 ; Palinkas, 2003 ; Gunderson & Nelson, 1963 ; Gunderson, 1968 ; Christensen & Talbot, 1986 ; Kanas, 1985 ; Kanas & Feddersen, 1971). Serxner (1968) a montré que l'incidence des réactions anxieuses, dépressives et psychotiques était d'environ 5% lors d'une patrouille sous-marine. Palinkas et al. (2001) ont rapporté que 5,2% d'un équipage d'hiver sur une période de quatre ans répondait aux critères d'un trouble DSM-IV après un hiver austral en Antarctique. Une variété de symptômes psychologiques et psychosomatiques apparait dans ces environnements exceptionnels. Ils comprennent, sans s'y limiter, des maux de tête (Earls, 1969 ; Natani & Shurley, 1974 ; Mulin, 1960 ; Serxner, 1968 ; Weybrew, 1961), des troubles digestifs (Kanas, 1985 ; Kanas & Fedderson, 1971 ; Palinkas & Suedfeld, 2008), des troubles du sommeil (Basner et al., 2015 ; Frantzidis et al., 2019 ; Palinkas, 1992 ; Weybrew, 1957), des variations de la thymie (Palinkas et al., 1995 ; Palinkas et al., 2004 ; Suedfeld & Weiss, 2000), des troubles cognitifs (Strange & Youngman, 1971 ; Ventsenostev, 1971 ; Natani et al., 1973 ; Kanas, 1985 ; Defayolle et al., 1985 ; Vaernes et al., 1993 ; Manzey et al., 1998 ; Kanas et al., 2013), une diminution des performances sensorimotrices (Peters et al., 1963 ; Manzey et al., 1993 ; Newman & Lathan, 1999 ; Pagel & Choukèr, 2016 ; Kim et al. 2018b).

Des troubles du sommeil ont été observés dans l'espace, notamment des caractéristiques telles que l'insomnie, la mauvaise qualité du sommeil, la fatigue et des altérations des cycles de sommeil. Ils ont également été signalés lors de missions sous-marines et antarctiques. Un sommeil d'une durée et d'une qualité suffisantes est d'une importance capitale pour des performances diurnes élevées. Toutefois, les astronautes participant à des missions de la navette spatiale et de la station spatiale internationale (*international space station*, ISS) ont dormi en moyenne moins de 6.1 heures par 24 heures. Cette quantité de sommeil est comparable à celle d'une restriction chronique du sommeil, dont il a été démontré qu'elle induit des déficits cognitifs et neurocomportementaux ainsi que des effets négatifs sur la santé. Les perturbations du sommeil peuvent également être liées à la dépression et à l'asthénie pouvant survenir durant la phase intermédiaire des vols spatiaux de longue durée (*long duration space flight*, LDSE) (Kanas, 1997). Palinkas (1990) a mis en évidence durant un hivernage une absence totale de sommeil de stade IV, des réductions considérables de la quantité de sommeil de stade III et de sommeil paradoxal ainsi qu'une perturbation des rythmes circadiens[5]. De même, Bhargava et al. (2000) ont rapporté des troubles du sommeil entre 24% et 80% des sujets dans une station polaire indienne. Ils étaient le plus nombreux au milieu de l'hiver. Il est à noter que les troubles du sommeil surviennent sur des individus n'ayant jamais rencontré ces difficultés au préalable (Mullin, 1960).

La plupart des avis tendent également à diverger sur la gestion des performances cognitives (Basner et al, 2015 ; Derayapa, 1971 ; Rivolier, 1997). Cependant, dans un monde où la plus petite erreur peut conduire à de graves accidents voire au décès, il est primordial que les capacités cognitives restent intactes. Aussi bien en Antarctique (Collins, 1985 ; Newkirk, 1990) que dans l'espace (Lugg, 1977 ; Palinkas, 1992 ; Rivolier, 1997), des études ont rapporté des erreurs de jugement et des mauvaises prises de décision. Des diminutions de la vigilance, de la concentration et de la mémoire chez les hivernants polaires ont également été montrées (Natani et al., 1973 ; Strange & Klein, 1973 ; Mullin, 1960). Manzey (1998) n'a pas révélé d'altération des fonctions cognitives pendant un vol spatial mais une possible altération des processus attentionnels induits par les exigences de l'environnement. Il conclut que les trois premières semaines après l'arrivée dans le nouveau milieu et les deux premières semaines de retour sur Terre seraient les phases les plus critiques. La stabilité de l'humeur et des performances observées après une adaptation réussie à l'environnement spatial indique que la cognition et l'état émotionnel peuvent être maintenus à un niveau aussi élevé que sur Terre, même pendant des LDSE. Newman (1999) n'a pas rapporté de baisse des performances cognitives mais une diminution des performances motrices. Manzey et al. (1993) ont trouvé des résultats similaires. Lors de séjours prolongés dans l'espace, une modification

[5] Le sommeil est constitué en cycles (i.e., 90 minutes environ) qui sont décomposés en deux types d'états : le sommeil paradoxal et le sommeil non paradoxal. Ce dernier comprend quatre stades à savoir l'endormissement (i.e., stade I), le sommeil léger (i.e., stade II), le sommeil profond (i.e., stade III & IV). Le stade I traduit la transition entre l'état de veille et de sommeil. Le stade II qui représente 50% du temps de sommeil alterne entre des périodes de tension et de relaxation musculaire, le rythme cardiaque y est ralenti et la température corporelle diminuée. Les stades III & IV qui constituent 20% du sommeil représentent la période où le sommeil y est le plus profond et réparateur. Le sommeil paradoxal désigne la phase durant laquelle le cerveau est actif, la respiration et le rythme cardiaque augmentés et irréguliers, les mouvements oculaires rapides et les muscles relâchés. Ce stade est associé aux périodes de rêves et intervient plusieurs fois au cours du sommeil en alternance avec le sommeil non paradoxal.

du système vestibulaire et somatosensoriel se produit (Bock et al., 2001 ; Demontis et al., 2017 ; Hallgren et al., 2016 ; Harris et al., 2010 ; Lackner, 1993). Il y a une altération de l'entrée des informations sensorielles due à une modification des stimuli d'accélération linéaire aux récepteurs otolithiques et essentiels à l'orientation spatiale sur Terre. Ceci a un impact sur l'équilibre postural, la vitesse de marche, la coordination tête-tronc (Black et al., 1995 ; Glasauer et al., 1995 ; Reschke et al., 1994). Black (1995) a montré un changement des références d'orientation somatosensorielles et visuelles lors du retour sur Terre.

Peu d'informations sont disponibles sur l'impact sensoriel des environnements ICE/EUE, où la monotonie sensorielle est profonde. Les astronautes ont une entrée sensorielle réduite, et donc des réponses sensorielles modifiées (Clement et al., 2020). Des changements réversibles modérés de la fonction visuelle ont été montrés dans certaines études en environnement polaire en raison de l'altitude (Barabasz & Barabasz, 1986 ; Bosch et al., 2010 ; Guly, 2012c ; Leach, 2016 ; Salam, 2020 ; Varyvonchyk et al., 2014) et dans l'espace en raison du mouvement des fluides du corps vers la partie supérieure (Lee et al., 2018 ; Mader et al., 2011 ; Patel et al., 2020 ; Zhang & Hargens, 2018). L'olfaction et le goût peuvent également être potentiellement perturbés lors d'un séjour dans l'espace (Newberg, 1994 ; Leach, 2016 ; Olabi et al., 2002). Une sensibilité accrue de l'audition a été signalée lors des missions russes Salyut-6 et Salyut-7 (Kelly & Kanas, 1992). Des modifications physiologiques et cérébrales ont également été observées (Angeloni & Demontis, 2020 ; Scheiner et al., 2012 ; Stahn & Kühn, 2021 ; Van Ombergen et al., 2017a, Van Ombergen et al., 2017b). Des études ont mis en évidence des changements structurels majeurs au niveau cérébral. Ces changements incluent une redistribution du liquide céphalo-rachidien, une diminution du volume ventriculaire et une diminution généralisée du volume de la matière grise (Patel et al., 2020 ; Stahn & Kühn, 2021).

Également, la perception du corps dans l'espace se trouve modifiée en situation gravitaire inversée. La gravité est par définition l'accélération présente sur Terre de l'ordre de ~9.81 ms^{-2}, exprimée en g. L'hypergravité inclut les niveaux de gravité au-dessus de 1 g. Inversement, « l'hypogravité » ou « gravité partielle » ou « gravité réduite », se définit par des accélérations inférieures à 1 g. Sur Terre, la perception de l'orientation du corps dans l'espace est définie par rapport à notre position dans l'environnement. Ainsi, une modification de l'orientation de la tête et du tronc par rapport à un environnement donné est directement en lien avec la perception de l'orientation de ce corps dans l'espace. En situation de microgravité ou 0 g, notamment lors de vols paraboliques ou orbitaux, des illusions d'orientation visuelle de même que des sentiments d'inversion de soi apparaissent (Graybiel & Kellog, 1967). L'orientation spatiale humaine et le contrôle sensorimoteur dépendent de manière critique de multiples signaux sensoriels et moteurs fournissant des informations sur les schémas d'activité musculaire en cours et leurs conséquences sensorielles. Les récepteurs otolithiques de l'oreille interne fournissent des informations sur l'orientation de la tête par rapport à la direction de la gravité, et les récepteurs du toucher ainsi que de la pression signalent la direction. La perception des organes otholitiques est à l'origine de mouvement réflexes des seuils, du tronc, de la tête et des membres (i.e., réflexes vestibulo-occulaires, réflexes vestibule-posturaux, réflexes vestibule-vasculaires). Des altérations du contrôle et de l'appréciation des mouvements associées à l'exposition à des niveaux de force gravitaires se produisent également pendant les vols spatiaux. Les astronautes sont soumis à une succession de g, alternant entre des forces positives et négatives. À chaque transition du niveau de force, des perturbations de l'orientation et du contrôle moteur se produisent. Au retour sur Terre, elles se manifestent sous la forme d'une instabilité apparente de la base d'appui pendant le mouvement, d'une sensation inappropriée des commandes, d'une sensation de lourdeur. Les mouvements d'orientation et de locomotion sont également affectés (Parker et al., 1989 ; Clarke & Schönfeld, 2015 ; Hallgren et al., 2016). Plus récemment, Reschke et al. (2017) ont mis en évidence, 1 à 5 heures après atterrissage d'un vol spatial de courte (1 semaine) et de longue (6 mois) durée, une marche instable et des instabilités posturales à un degré qui limiteraient la capacité des membres de l'équipage à sortir du vaisseau spatial par eux-mêmes dans les premières heures suivant l'atterrissage. L'anomalie la plus courante était l'incapacité de marcher du talon aux orteils sur une ligne droite sans trébucher ou tomber. En somme, les réactions physiologiques sous accélérations sont encore peu comprises (Goswami et al., 2021).

L'ensemble de ces symptômes ne dépendent pas uniquement du temps qui passe, ni de la durée de la mission (Gunderson, 1968 ; Kanas & Feddersen, 1971 ; Le Scanff et al., 1997 ; Manzey et al., 1993 ; Strange & Klein, 1974). Il existe des preuves empiriques de l'existence de périodes cruciales spécifiques qui se produisent approximativement au milieu et vers la fin du séjour dans les stations polaires (Palinkas et al., 1998), à bord d'un sous-marin nucléaire lanceur d'engins (*sub-surface ballistic nuclear-powered missile submarines*, SSBN) (Sandal et al., 2003) ou d'un vol spatial (Connors et al., 1985). Une revue de Guly (2012b) mentionne trois syndromes au sein d'un hivernage polaire, chacun présentant des caractéristiques spécifiques. Strange et Yougman (1971) ont décrit un ensemble de symptômes de dépression, d'hostilité, de troubles du sommeil et de troubles cognitifs, appelé « syndrome de l'hiver ». De plus, les symptômes semblent augmenter après le milieu de la mission, avec une certaine réduction des symptômes vers la fin. Ce schéma est connu sous le nom de phénomène du troisième quart (Bechtel & Berning, 1990). Néanmoins, l'évidence d'un phénomène du troisième trimestre est largement discutée au sein de la communauté scientifique, où les études ne le rapportent pas systématiquement (Gazenko, 1982 ; Palinkas et al., 1998). Le syndrome polaire T3 correspond à des modifications de la fonction thyroïdienne avec des répercussions sur les performances cognitives et l'humeur. Il a été signalé lors de plusieurs hivers polaires et est caractéristique de cet environnement (Guly, 2012b ; Palinkas & Suedfeld, 2008). La dépression saisonnière liée aux changements de photopériodicité induit une augmentation des symptômes dépressifs. Bien qu'ils soient fréquemment signalés, ces symptômes conduisent rarement à un traitement (Palinkas & Suedfeld, 2008). Une revue de 2011 (Leon et al., 2011) indique que cette dépression serait liée au froid et au stress psychosocial vécu dans l'environnement. Palinkas et al. (2021) l'ont associé aux concentrations circulantes de mélatonine.

Ces symptômes peuvent différer d'une station polaire à l'autre. Au cours de l'hivernage de 1989 à la station américaine McMurdo, 64,1% des membres d'équipage ont déclaré avoir eu des problèmes de sommeil, 62,1% s'être sentis déprimés, 47,6% s'être sentis plus irritables qu'en temps normal et 51,5% avoir rencontré des difficultés de concentration ou de mémoire (Palinkas, 1992). Majoritairement, les types de troubles mentaux les plus courants dans les stations américaines en Antarctique étaient la dépression, l'abus d'alcool, la paranoïa et les troubles psychosomatiques (Strange & Klein, 1974). Taylor et Feletti (1976) ont étudié 30 hommes qui avaient passé l'hiver dans l'une des deux stations australiennes entre 1969 et 1972. Les hommes dont les performances ont été jugées médiocres pendant leur séjour ont obtenu des scores plus élevés en matière d'appauvrissement émotionnel, d'attitude revêche, d'inefficacité relative au travail et d'aliénation du groupe que ceux dont les performances ont été jugées bonnes. Sasaki et al. (1980) ont étudié les facteurs psychologiques chez 30 membres hivernant dans une station japonaise. Les scores moyens de l'Inventaire d'anxiété d'état et de trait étaient stables pendant que les membres étaient à bord du navire de transport, mais ils ont augmenté juste après l'arrivée à la station et ont continué à augmenter au fil du temps. Les scores d'anxiété et de dépression étaient les plus élevés au cours des trois derniers mois du séjour.

L'ensemble de cette symptomatologie démontre un effet pathogénique des milieux extrême sur l'état de santé des individus qui y séjournent. Qu'en est-il alors de cet impact depuis les années 2005 ? Alors que les conditions de vie sur la majorité des stations analogues ont pu être considérablement améliorées, est-ce que la mise à jour de ces terrains a un impact sur les réponses adaptatives des équipages ? Également, face à la multitude des terres analogues depuis les années 80, est-ce que toutes les missions à bord de stations en milieu ICE et/ou EUE ont vocation à être rapprochées de l'environnement spatial ?

Une partie de ces questions a vocation à être abordée au sein d'une revue de la littérature (PRISMA) se voulant récente conduite dans le cadre de ce travail de Thèse. Celle-ci avait trois objectifs principaux : (1) résumer la littérature sur l'impact des ICE/EUE sur l'adaptation humaine à partir d'un cadre pluridisciplinaire physiologique, biologique, neuroscientifique, comportemental, cognitif et psychologique ; (2) identifier les processus psychocognitifs et les mécanismes neuronaux que les professionnels développent pour s'adapter à ces environnements exceptionnels ; et (3) étudier les différences et similitudes entre les analogues spatiaux en termes de leurs impacts sur l'adaptabilité humaine.

Human challenges to adaptation to extreme professional environments: A systematic review

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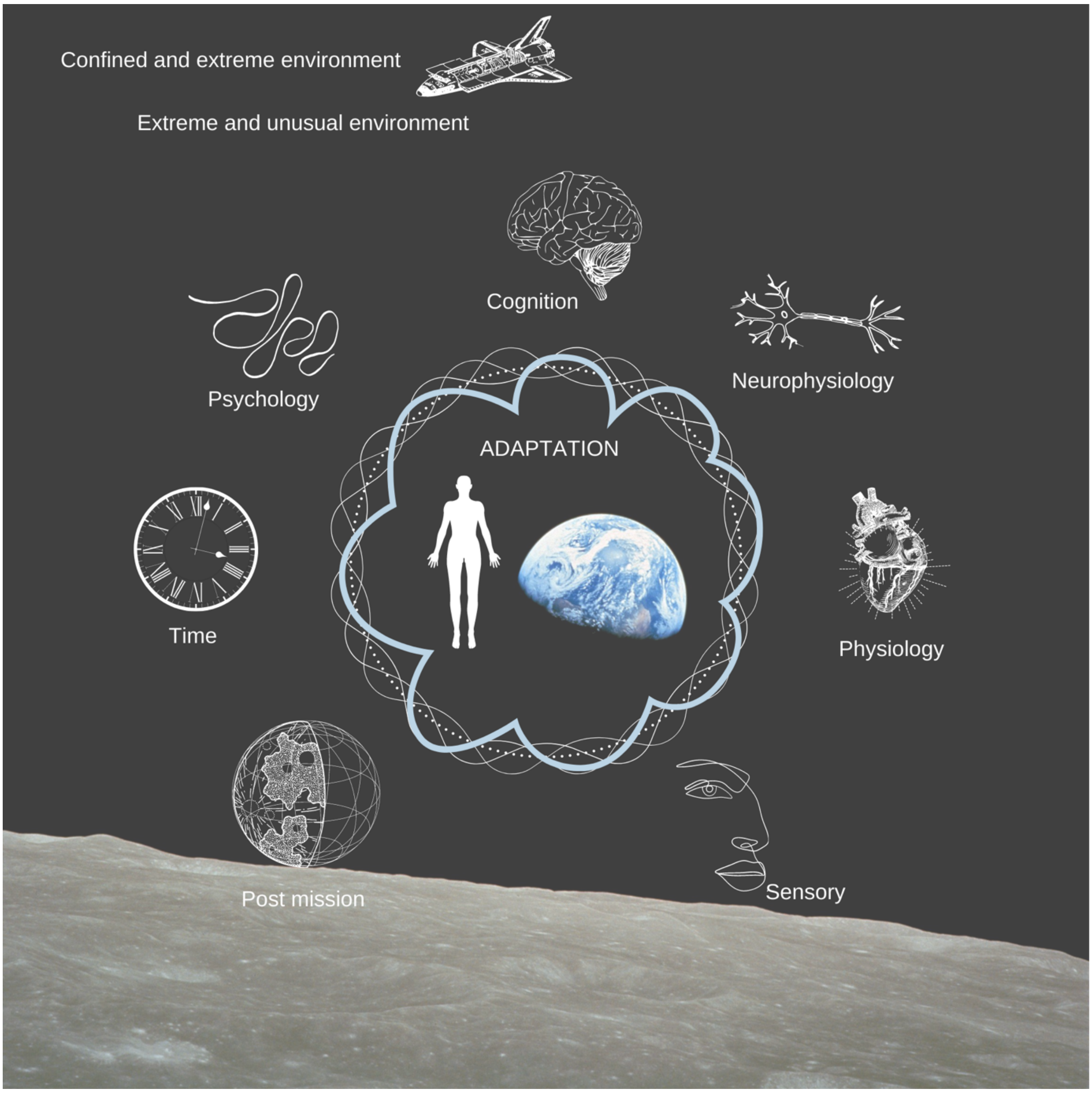
Abstract

NASA is planning human exploration of the Moon, while preparations are underway for human missions to Mars, and deeper into the solar system. These missions will expose space travelers to unusual conditions, which they will have to adapt to. Similar conditions are found in several analogous environments on Earth, and studies can provide an initial understanding of the challenges for human adaptation. Such environments can be marked by an extreme climate, danger, limited facilities and supplies, isolation from loved ones, or mandatory interaction with others. They are rarely encountered by most human beings, and mainly concern certain professions in limited missions. This systematic review focuses on professional extreme environments and captures data from papers published since 2005. Our findings provide an insight into their physiological, biological, cognitive, and behavioral impacts for better understand how humans adapt or not to them. This study provides a framework for studying adaptation, which is particularly important in light of upcoming longer space expeditions to more distant destinations.

Figure 15
Graphical abstract PRISMA



Keywords

Adaptation, Extreme and Unusual Environment, Health, Isolated and Confined Environment, Neurosciences, Stress

1. Introduction

« At the closing of this century, Homo sapiens might well be described as an interstitial species. We are not just between two time periods, but between two ways of life. As we make the transition into the 21st century, humankind is being transformed from a terrestrial to an extraterrestrial being. In the process of this transformation, our species will be changed both physically and psychologically. The survival of the species in outer space demands significant adaptation to differing environmental realities » Harris (1989).

On July 20, 1969, the world held its breath as American astronaut Neil Armstrong became the first man to set foot on the Moon. More than 50 years later, interest in space has been renewed by the exploration of Mars. Although views differ, space missions are vectors for major technological and scientific advances. A key development, in this new era, is that partnerships with private companies are driving progress. SpaceX became the first private entity to refuel the International Space Station (ISS) and, more recently, transport space travelers (November 16, 2020). Although space agencies were planning a permanent human presence not only onboard the ISS, but also the Moon and Mars (Harrison et al., 1989; National Commission on Space, 1986) in the 1990 s, according to NASA Administrator Jim Bridenstine, a return to the Moon is not expected until around 2024, followed by a mission to Mars around 2033. A journey to Mars would require space travelers to spend nearly three years in space and, during this time, they will be confronted with extreme physiological and psychological conditions. Although nearly 600 space travelers have already been in space, fewer than ten have stayed for a significant period of time (i.e., missions usually do not last longer than six months, even though increasingly records are being achieved). It is therefore urgent to evaluate and understand the impact of a long space flight on the physiology and psychology of human beings.

1.1. Beyond the stars: the hazards of space

Space is a naturally hostile environment. Space travelers onboard the ISS are isolated for around six months to one year from the ‘normal’ world (Collet & Vaernes, 1996), and spend most of their time working. Space is characterized by weaker gravity and various physical and psychological stressors (Borchers et al., 2002). It places high demands on their resources and can compromise performance. Physical stressors include the 90-minute orbit of the ISS, which means that the day is artificially divided into 16 sunrises/sunsets; gravitational forces during launch and landing, vibration, noise, microgravity, radiation, increased microbial load, and malnutrition due to motion space sickness. Psychological stressors include anxiety related to the danger of the mission and the hostile environment, the inability to return to Earth, the intense workload, isolation from family, friends and normal social settings, and the difficulty of living together as a small group for a long period.

These space stressors have long-term repercussions. Microgravity is cited most often. Effects include physiological changes in vestibular input, and bone and mineral metabolism, a shift of fluids to the upper parts of the body, and disturbed proprioceptive processes (Bettiol et al., 2018; Clément, 1998; Grimm et al., 2016; Hughson, 2018; Nicogossian et al., 1994; Patel, 2020; Van Ombergen et al., 2017a; Van Ombergen et al., 2017b; Vernikos, 1996). However, astronaut Norm Thagard reported that during the Mir-18 mission, psychological stress, isolation, and confinement were the main challenges (Lugg & Shepanek, 1999). Manzey et al. (1998) developed new categories of stressors that include the space habitat and its life support system (e.g., confinement, high levels of ambient CO2 and noise), workload (both physical and mental), and social aspects (e.g., lack of privacy, distance from loved ones) (Manzey et al., 1998). Furthermore, risk is an integral part of the mission. The inhospitable space environment can quickly become the only sanctuary if there is an equipment malfunction, or a collision with an external object (Connors et al., 2005).

1.2. Extremes on Earth: a challenge for research

Space travelers who travel to another planet or participate in a long-term space mission are confronted with a harsh environment. The multitude of constraints they face are difficult to replicate on Earth. However, there are some terrestrial environments that can be used to study and predict the effects of long-duration space travel on the human body.

Manzey and Lorenz (1998) define extreme environments as, « settings that possess extraordinary physical, psychological, and interpersonal demands that require significant human adaptation for survival and performance » (Manzey & Lorenz, 1998). These environments share several characteristics – notably constant danger, the need for a high-tech life support system, a lack of space, isolation, discomfort, lack of external visibility, specific clothing, unusual photoperiodicity, lack of intimacy, and possibility of sudden disaster. Often cited as Isolated and Confined Environments (ICE), or Extreme and Unusual Environments (EUE) (Suedfeld & Mocellin, 1987), they have also been named 'strange', 'exotic', 'abnormal', or 'stressful environments' (Bachrach, 1982; Harrison & Connors, 1984; Ross, 1974). Suedfeld (2000; 2018) differentiated the characteristics of ICE and EUE. The physical parameters of EUE do not allow humans to survive, giving them an aura of rarity and exoticism, or even fear and wonder. They often require sophisticated, and high-tech survival systems. The failure of which can lead to death. ICE may be a specific category of EUE, which feature physical remoteness or a lack of access to other locations. Whether permanent or temporary, they can be termed 'extreme' due to the temperature, altitude, level of danger, lack of access to food, water, shelter, and other resources necessary for safety and comfort. These ICE and EUE environments are extremes.

Extreme environments on Earth include polar stations, Sub-Surface Ballistic Nuclear-powered missile submarines (SSBN), expeditions, and simulations of future space missions (Bishop, 2013; Botella et al., 2016; Feichtinger et al., 2012; Kanas, 1990; Lugg, 2005; Schlacht et al., 2016; Shepanek, 2005; Suedfeld, 2010; Suedfeld & Steel, 2000; Tortello et al., 2018; Ursin, 1991; Van Ombergen et al., 2021; Wharton et al., 1990). They are usually related to the space environment and used as 'space analogs'. More specifically, analogs are environments that aimed to support or simulate space missions. Thus, they share common characteristics with the space environment and the population target to prepare future space mission (Binsted et al., 2010; Lebeuf, 2008). Individuals who spend time in them require complex support operations to survive and be autonomous. In the context of space exploration, future space travelers must be selected, prepared for, and protected from the negative effects of the extreme conditions they will encounter (Pagel & Choukèr, 1985). The Antarctic is typically considered a natural laboratory for the study of the effects of isolation and confinement on human behavior (Suedfeld & Weiss, 2000; Shurley, 1974). This ice desert is one of the coldest and most hostile places on the planet, and many scientific studies have been run since its discovery (Bruguera et al., 2021; Gunderson, 1974a; Gunderson, 1974b; Palinkas, 1992; Palinkas and Suedfeld, 2008; Suedfeld, 1991; Taylor, 1987; Van Ombergen et al., 2021). Polar winterers are exposed to around 24 h of daylight during the austral summer, and around

24 h of darkness during the austral winter. Like the space environment, time spent in Antarctica is characterized by prolonged isolation, confinement with a small number of individuals, monotony, sensory deprivation, extreme temperatures, and no way to escape, among other factors. More recently, the SSBN is another environment considered as a faithful analog of a space mission (Sauer et al., 1996). Due to their similarities, several parallels can be drawn between an SSBN and a space habitat: (1) autonomous crews, (2) pressurized life capsule, (3) major disasters in case of loss of power, (4) monitored indoor temperatures and radiation levels, (5) distilled and reused water, (6) regenerated and cleaned atmosphere, (7) significant risk of fire and toxic smokes, (8) confined and limited space, (9) significant noise levels, (9) crew members limited, (10) and heavy workload (Earls, 1991; Kanas, 1987; Sandal et al., 2006; Ursin et al., 1991; Weybrew, 1991; Weybrew & Molish, 1986).

1.3. Exploring analogs: a response to the need for studies in ecological environment

Studies in an ecological environment are a unique opportunity to collect data that a traditional research laboratory cannot provide. Although they require the implementation of advanced technologies to ensure the protection and maintenance of life in a life-threatening environment. Their extreme nature provides valuable information about human adaptive capabilities. Polar stations and SSBN are examples of ecological environments that have similar requirements in terms of selection procedures, nature of the work, and crew composition. Furthermore, the risks are high, and the costs associated with failure. There are multiple critical interfaces (i.e., human-human, human-technology, and human-environment), and critical requirements regarding coordination, cooperation, and communication within the team (Bishop, 2006; Davis et al., 2021). Polar bases are particularly useful, as they can provide access to more participants. Data are plentiful, meaning that results are more generalizable, and have a greater impact within the scientific community. Cost is another significant factor (Harrison et al., 1991; National Research Council, 1998; Palinkas, 2003; Rivolier, 1997). Analog environments can lower these costs and facilitate the implementation of long-term experiments. The latter is an essential consideration for future long-duration space missions. Space travelers currently spend an average of six months onboard the ISS, but a journey to Mars would take about two years and a half.

In general, analog environments provide high-fidelity, standardized experimental conditions (Pagel & Choukèr, 2016). They enable in-depth evaluations of the effects of physiological and psychological changes on human health and can help address specific problems related to space missions (Yuan et al., 2019). However, several key aspects of the space environment cannot be replicated. Microgravity and the risk of radiation are difficult to assess on Earth. These risks vary greatly with respect to both the degree, and the nature of the challenges they present to individuals, especially on Mars (Kanas et al., 2007) where distance plays an important role (Retm, 2015). Furthermore, there are clear differences at the individual level, and between analogs. The number of crew members is very different, as their social and demographic characteristics (Palinkas et al., 2000b; Suedfeld & Weiss, 2000). Other aspects cannot be replicated, notably the level and source of danger. The distance from Earth is another aspect that is specific to space missions. On the one hand, space travelers do not necessarily have access to support from the ground. On the other hand, analog studies of physio-psycho-cognitive responses cannot truly reflect the extraordinary reality of space. One example is the impact of the Earth-out-of-view phenomenon on the psyche of individuals. Deep in the vacuum of space, Earth will be so far away that it will become a memory. Kanas (2005) suggests that the consequence could be a deep feeling of loneliness and isolation. Effects could range from a restructuring of the conception of humanity's place in the cosmos, to no impact at all. Overall, these issues compromise how faithfully analogs can replicate long-term space missions.

1.4. Extreme stressors and adaptation: similarities with space

Herman and Cullinan (1997) characterized space flight and analogs by the presence of systemic (e.g., hypoxia, noise, isolation) or processive (e.g., lack of privacy, monotony, fatigue) stressors. They represent two different stress pathways that differ in both their temporality, function and cerebral structures involved. Systemic stressors involve immediate physiological threat and thus survival response through a direct pathway to the hypothalamic paraventricular nucleus. Processive stressors have no temporality. They imply a « high-order sensory processing » through the limbic system, using multimodal stimuli that are confronted to previous experiences and labelled « stressful » or « unstressful ». These repeated, multiform, and combined factors can induce high levels of stress, with adverse consequences on health (Cunha et al., 2021; Décamps &

Rosnet, 2005; Farrace et al., 1999; Harrison et al., 1989; Orasanu & Lieberman, 2011; Salam, 2020; Stuster, 2010; Stuster et al., 2000; Suedfeld & Weiss, 2000; UK report, 2019) and increased operational risks, as long-term stress tends to degrade human performance (Suedfeld, 2001). While studies of crew members onboard a SSBN report higher levels of cortisone compared to baseline, and higher levels of stress during the mission (Sandal et al., 2003), we still know little about how stress is experienced by individuals in ICE/EUE.

Sources of stress in ICE/EUE can be divided into five, interacting categories (McPhee & Charles, 2009; Sandal et al., 2006; Smith & Barrett, 2018; Suedfeld & Steel, 2000; Vakoch, 2011, 2013; Vanhove, 2014). (1) Environmental stressors relate to the harsh environment. They include microgravity, radiation, extreme temperatures, noise, the atmospheric composition (i.e., helium-oxygen mixtures that increase the risk of fire, CO2 levels), monotony, isolation, altitude, and light-dark cycles. (2) Physical and psychological stressors relate to the confined environment. They include limited space, separation from loved ones, a lack of privacy, psycho-cognitivo-emotional challenges, somatic problems, loss of body heat, increased risk of ear infections, the absence of an opportunity to withdraw or escape from the situation, sensory restriction, and overwork. (3) Social stressors relate to interpersonal relations. They include conflict, social monotony, communication, leadership, crew size, gender, or culture. (4) Seasonal stressors relate to the passage of time. One critical characteristic is the mission length, due to its interaction with physical and psychological stressors. Not only are there critical phases (e.g., after the halfway point), but there are also cumulative effects whose long-term impacts can be significant. In this review, we focus on temporal aspects these seasonal effects are not dependent of these environments. (5) Post mission stressors relate to the re-entry shock after a long time away. Experience shows that it can be difficult to readjust to normal life. Problems can be physical, especially for space travelers, who are unable to stand. They can also be familial. Long periods of separation can be difficult for couples. Submariners, for example, experience ‘submariners wives’ syndrome (Glisson et al., 1980; Isay, 1968). Finally, personality changes can occur (Frantzidis et al., 2019; Kanas et al., 2009; Retm, 2015). Table 1 summarizes the major stressors experienced by individuals in ICE and EUE. Analogs are thus spaces close to the space environment because they challenge the man who settles there to adapt to close or even similar stressors. These analogues challenge the possibilities of human adaptation just as space does.

Table 1

The major stressor in ICE/EUE

Stressor	Environment*
Perpetual danger	Spacecraft, polar station, submarine, expeditions
High-tech life support system	Spacecraft, polar station, submarine
Confinement	Spacecraft, polar station, submarine, caves
Isolation	Spacecraft, polar station, submarine
Physical discomfort	Spacecraft, polar station, submarine, caves, expedition
Protective clothing	Spacecraft, polar station, submarine
Photoperiodicity	Spacecraft, polar station, submarine, simulation, caves
Lack of intimacy	Spacecraft, polar station, submarine, simulation, caves
Possibility of sudden disaster	Spacecraft, polar station, submarine, expeditions
Cross-cultural differences	Spacecraft, polar station, expeditions, simulation
Demanding work	Spacecraft, submarine, simulation
Dream time	Polar station, expedition, caves
Unusual circadian rhythms	Spacecraft, polar station, submarine
Limited communication	Spacecraft, polar station, submarine, expedition, caves
Sensory deprivation	Spacecraft, polar station, submarine, simulation, caves
Monotony	Spacecraft, polar station, submarine, simulation, caves
Radiation	Spacecraft, submarine
Microgravity	Spacecraft
Noise	Spacecraft, polar station, submarine
CO2	Spacecraft, submarine, simulation
Temperature	Spacecraft, polar station, submarine
High altitude	Polar station, expeditions
Humidity	Spacecraft, submarine, expeditions, caves
Similar duty rotation	Spaceflight, polar station, simulation
Limited supplies and equipment	Spacecraft, polar station, submarine, simulation

*This list is not exhaustive. Only the most frequently mentioned stressors are reported.

Let humans live in space raises the question of adaptation and thus, the preservation of the state of homeostasis retrieved in a new environment of life. Adaptation is a dynamic, polysemic and multidisciplinary concept of evolution of the species and thus of natural selection which attempts to determine the probability of survival of an organism. In order to avoid any confusing aspect regarding the definition of adaptation, we use this term to refer a process that delivers positive and successful health outcomes. Obviously, adaptation does not allow to adjust with the physical requirements of the environment but only acclimatization (i.e., physiological, biochemical, and anatomical changes in an individual after exposure to a new environment from days to months) (Williams et al., 2009). For mammals, acclimatization refers to a coordinated response to single or concomitant stressors (e.g., temperature, gravity, photoperiod). It acts to improve fitness to the environment. Adaptation explicitly recognizes that stressor-strain relationships unfold over time. Health is an inherent state from adaptation/acclimatization, defined by different factors in such extreme environments: temporal, psychiatric, psychological, cognitive, physiological, neurophysiological, sensory, and post-mission. Changes constitute stressors to which everyone's response to adjust and/or recover is interdependent (Selye, 1956). They underline the importance of interactions between humans and their environment. The effectiveness of the response is the key to ensure health (Lazarus & Folkman, 1984). Humans can only remain in a healthy state by trying to minimize the cost of interaction with the environment. Thus, the quality of the interactions plays a fundamental role in acclimatization and adaptation; on which health depends. Nevertheless, it is essential to emphasize that the people involved in these extremes have chosen to work there. It is a commitment and a professional choice that is not undergone, as could be the case in the SARS-COV2 pandemic.

1.5. Ending the challenge: a human confrontation

The first data on human adaptation in ICE/EUE date back to the 'heroic' age (Gunderson, 1966; Gunderson & Nelson, 1963; Mocellin & Suedfeld, 1991; Mullin, 1960; Palinkas, 1991; Ursin, 1991). Gunderson (1966) Gunderson (1968) was one of the first researchers to investigate the response of the organism in a polar environment. Diaries recovered from Scott's tragic expedition provide valuable information about survival (Halsey & Stroud, 2011; Halsey & Stroud, 2012), notably the role of extreme cold, falling body temperature, loss of weight, and a lack of food (Cherry-Garrard, 2013; Halsey & Stroud, 2011; Huntford, 2007; Rothblum, 1990). Studies aboard nuclear submarines (Earls, 1969; Horowitz, 1964; Weybrew, 1957a), and the first spaceflights (Berry, 1973; Garshnek, 1989; Harris, 1989; Peters et al., 1963; Santy, 1983; Smith, 1990) followed, along with simulations in confined situations (Coburn, 1966; Fraser, 1968). In general, the literature reports psychiatric symptoms such as anxiety and depression (Christensen and Talbot, 1986, Gunderson, 1968, Gunderson and Nelson, 1963, Kanas, 1985; Kanas et al., 1971; Palinkas et al., 1995). Serxner (1968) found that the incidence of anxious, depressive, and psychotic reactions was about 5% during a submarine patrol. Later, Palinkas et al. (2001) reported that, over a four-year period, 5.2% of a crew met the criteria for a DSM-IV disorder after an austral winter in the Antarctic. In space, a review reported two psychiatric events onboard the Mir space station (Shepanek, 2005).

The literature highlights a variety of other psychological and psychosomatic symptoms in ICE/EUE. These include, but are not limited to headaches (Earls, 1969, Mullin, 1960; Natany and Shurley, 1974; Serxner, 1968; Weybrew, 1961), digestive problems (Kanas, 1985; Kanas and Feedderson, 1971; Palinkas and Suedfeld, 2008), sleep disturbances (increased sleep latency, decreased sleep efficiency, reduced delta-sleep duration) (Basner et al., 2015; Frantzidis et al., 2019; Palinkas, 1992; Weybrew, 1957b), thymic variation (Palinkas, 1995; Palinkas et al., 2004; Suedfeld & Weiss, 2000), cognitive impairment (Defayolle et al., 1985; Kanas, 1985; Manzey et al., 1998; Natani et al., 1973; Strange & Youngman, 1971; Vaernes et al., 1993; Ventsenostev, 1973), and poorer sensorimotor performance (Kim et al., 2018; Manzey et al., 1993; Newman & Lathan, 1999; Pagel & Choukèr, 2016; Peters et al., 1963).

Empirical evidence suggests that these symptoms would not be a function of the passage of time (Gunderson, 1968; Kanas & Feddersen, 1971; Le Scanff et al., 1997; Manzey et al., 1993; Strange & Klein, 1974). Palinkas and Suedfeld (2008), Palinkas and Suedfeld (2021) listed three syndromes as: winter-over syndrome (i.e., characterized by sleep disturbance, cognitive impairment, and negative affect which tends to worsen in the third quarter); polar T3 syndrome (i.e., a state of relative hypothyroidism of the central nervous system, accompanied by systemic euthyroidism); and Subsyndromal seasonal Affective Disorder (SAD, i.e., an increase in depressive symptoms related to a change in photoperiodicity). There appear to be specific, crucial periods that occur approximately halfway through, and toward the end of the stay in polar stations (Palinkas et al., 1998), onboard a SSBN (Sandal at al., 2003), or during a space flight (Connors et al., 1985). Strange and Youngman (1971) describe a cluster of symptoms of depression, sleep disturbance, and impaired cognition, which they referred to as winter-over syndrome. In some cases, symptoms increase after the midpoint of the mission, with a reduction toward the end, a pattern that has been called the third-quarter phenomenon (Bechtel & Berning, 1990). However, many studies have failed to find confirmatory evidence (Gazenko, 1983; Palinkas et al., 1998). Despite a noticeable deterioration in health, there appears to be few long-term, negative effects.

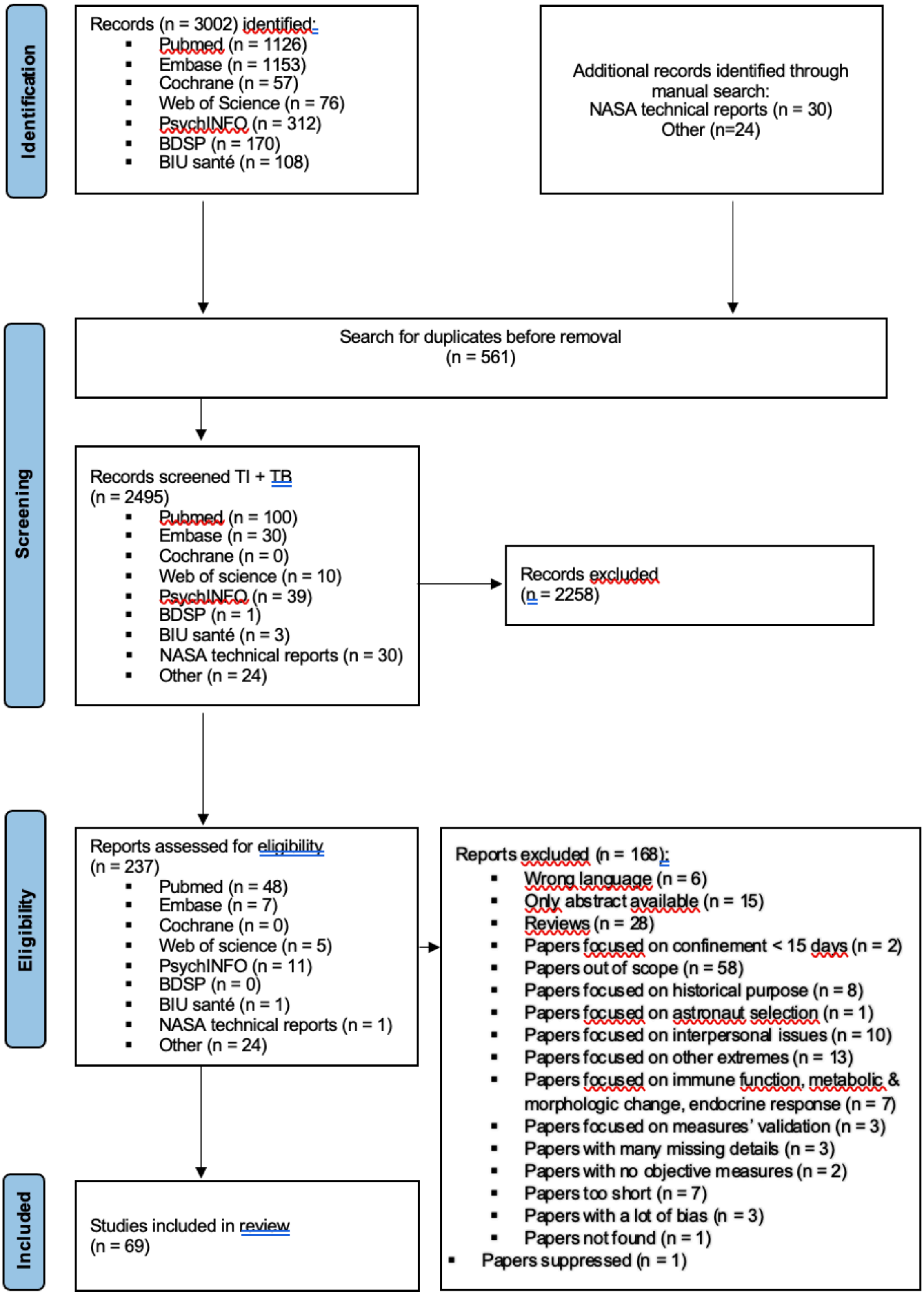
Almost 20 years ago, humans were already trying to find a way to reach Mars. In 2006, Robert Zubrin, President of the Mars Society and advocate of the Mars Direct plan, stated that humans would definitely be sent to Mars within 10 years (Emurian & Brady, 2007). The 2004 Garriott-Griffin report on strategy for the American space exploration policy stated that humans could land on the Moon or Mars as early as 2020 (Zubrin, 2000). The technological and human challenges are considerable. Even if the history of manned space missions has shown that humans can endure such conditions for up to a year, few space travelers have spent more than six months in space. In recent years, multiple studies have investigated the question. However, we still do not know enough about the risks of long-duration space missions, nor what can be done to effectively mitigate them. Although most reported problems are relatively minor, they can be mission-threatening. Faced with a hostile event, there is no way to escape.

The principal aim of this systematic review is, therefore, to summarize the literature on the impact of ICE/EUE on human adaptation, from a broader study framework (i.e., physiological, biological, neuroscientific, behavioral, cognitive, and psychological. A secondary aim is to identify the psycho-cognitive processes, and neural mechanisms that professionals develop to adapt to these exceptional environments. A third, exploratory aim is to investigate the differences and similarities between space analogues (i.e., represented by ICE and EUE environments) in terms of their impacts on human adaptability. Finally, these three objectives allow us to discuss the adaptation frameworks for spatial and analogs environment to enrich the knowledge on human adaptation in ICE/EUE environment.

2. Materials and methods

Our study was based on the Preferred Reporting Items for Systematic Reviews and Meta-Analyses (PRISMA) standard (Moher et al., 2010). The protocol was registered with the international prospective register of systematic reviews (PROSPERO) on 24.02.2021 (registration number CRD42021232296). Fig. 1 outlines the review process and findings.

Figure 1
PRISMA flow chart



2.1. Search strategy

Seven electronic databases were screened (MEDLINE, Embase, PsycINFO, the Cochrane Library, the Banque de données en santé publique, the Web of Science, and the NASA Technical Reports Server) for scientific studies examining the impact of ICE/EUE on individuals. A manual search of online resources provided by the Medical Library of Paris Descartes University (France) and Google Scholar identified additional relevant studies. Only studies published between January 2005 and November 2021 were considered, in either English or French. The following search terms were used:

2.1.1. Group 1: population studied

Submariner, submarine medicine, medicine submarine, astronaut, cosmonaut, spationaut, spatial exploration, exploratory spatial, medicine space, space medicine, medicine aerospace, aerospace medicine, space simulations, orbital simulations, simulation space, orbital simulation, space simulation, polar expedition, polar base, polar station, polar expeditions, polar bases, polar stations, polar team, polar teams, antarctica, Antarctic, Arctic, Concordia, space environment, space environments, space habitation, space habitations, space travel, space travels, space travelers, space exploration, space explorations, space mission, space missions, spaceflight, spaceflights, space flights, flights, space, space flight, flight, space, space travels, space travel, lunar, Mars, interplanetary, environment, extraterrestrial, extraterrestrial environments, extraterrestrial environment, space crafts, space craft, spacecrafts, spacecraft, HISEAS, human exploration research analog, desert research and technology studies, desert rats, NASA.

2.1.2. Group 2: phenomena studied

Confined, confinement, isolated, isolation, extreme, unusual, sensory deprivation, deprivation, sensory, sensory deprivations, perceptual isolation, restricted environmental, enclosed habitat, enclosed habitats, enclosed environment, enclosed environments.

2.1.3. Group 3: consequences of the phenomena

Behavior, behaviors, sleep, sleeping, thymia, mood, moods, amnesia, memories, memory, concentrations, attentions, attention, concentration function, concentrate, concentration, concentrating, mental concentration, concentrated, attention function, emotional changes, cognitive, cognitive impairment, impairments cognitive, cognitive impairments, cognitive dysfunction, impairment cognitive, cognition, stresses, stress, sensory perceptions, sensory perception, sense, senses, adaptability, psychologic adaptation, adaptation psychological, behavior coping, behaviors coping, skill coping, behavior adaptive, adaptive behavior, coping behavior, skills coping, coping behaviors, adaptation psychologic, coping skill, coping skills, adaptive behaviors, behaviors adaptive, psychological adaptation, physiological adaptations, physiologic adaptations, physiological adaptation, adaptation physiological, physiologic adaptation, adaptations physiological, biologic adaptation, adaptation biological, adaptation biologic, biological adaptation, interoception, exteroception, position senses, proprioception, position sense, sense position, proprioception, sense of position, alertness, psychological.

2.2. Study selection and eligibility criteria

First, the title and abstract of each publication were checked for relevance. Full-text articles were evaluated for eligibility after this initial verification. The study's authors were contacted, if necessary, to resolve any questions. Any disagreement was resolved through discussion, and the reasons for excluding studies were recorded. Finally, additional studies were identified by cross-referencing the bibliographies of selected articles. None of the present review's authors were blind to the journal titles, or to the authors or institutions of the selected studies.

Given the lack of research, all study designs were considered. However, those with a high level of evidence were preferred. The following selection criteria were applied. (1) Those that examined a healthy, professional, adult (aged between 18 and 65) human population, working in an ICE/EUE, (2) run in an ICE/EUE or simulation, and (3) addressed the impacts and/or factors that influence individual adaptability to these environments. Factors included biological, physiological, neural, cognitive, and psychological outcomes (e.g., performance, health, emotions, mood, sensoriality, physiology), based on standardized measurements and validated scales. Sleep and fatigue studies were considered if they addressed individual differences in physiological or behavioral outcomes. ICE and EUE included space or space simulations, polar regions, submarine and underwater scenarios, military operations, and, if applicable, cave exploration. Finally, (4) only studies published between January 2005 and November 2021 were considered. The main part of the articles on ICE/EUE were published before this period. Thus, in an effort (1) to have a recent, and representative overview of the latest advances in this field of research, but also (2) to consider the current challenges for long space missions, we thought it is important to provide this selection.

A study was excluded if: (1) it was not run in space or an analog environment, (2) it was not written in French or English, (3) it only considered impacts and adaptability at team or group level, (4) the protocol was not specified; (5) it used animals as subjects, (6) the full-text was not available, (7) it did not focus on active professionals, (8) it focused on pathological populations, (9) it focused on cellular and molecular levels, (10) it focused on immune function, (11) it focused on microbiome, or (12) it examined missions of less than 15 days.

2.3. Data extraction

Data were extracted by two reviewers (BL, CMK) and checked by another (MT) for accuracy. All potential articles were downloaded as full text and stored in a shared folder. Three of the reviewers (BL, CMK, MT) reviewed each article independently to ensure that only relevant entries were included. Published articles were recorded in a Microsoft Excel (Microsoft Corporation, Redmond, WA, USA) spreadsheet to facilitate visibility. The following data were captured: (1) title, (2) authors, (3) year of publication, (4) citation, (5) type of publication, (6) country of origin, (7) objective, (8) inclusion/exclusion criteria, (9) age of participants, (10) gender, (11) ethnicity, (12) sample size, (13) method, (14) type of environment, (15) environment characteristics, (16) length of time in the environment, (17) measures/tools used, (18) outcomes, (19) limits, and (20) conclusion.

2.4. Methodological quality and level of evidence

Studies were assessed for fidelity/similarity to long-duration space missions using an adapted version of the Palinkas et al. (2011), and Bartone et al. (2018) scales (Table 2). It should be noted that Bartone et al. (2018) modified the initial Palinkas et al. (2011) methodology. Specifically, the former authors added a rating in Category A (similarity to spaceflight) to identify studies that included aspects of ICE environments but could not be considered as analogous to spaceflight. The total fidelity score represents the sum across four categories, and our review only considered studies that could be considered as analogous to spaceflight. With respect to Category C (similarity with respect to the duration of the mission), we considered missions lasting from 31 to 364 days, divided into two groups of either up to six months, or up to one year. This decision followed earlier work, which suggests that the impact of the mission differs for these periods. Two of the reviewers (BL, CMK) scored each study. Any disagreements were resolved first by discussion, and, if necessary, by consulting a third author (MT). Scores on the fidelity scale had a theoretical range of 4–13.

Table 2

Fidelity of studies compared to long-duration space missions

Category*				
Similarity to spaceflight		Spaceflight	Space simulation	Analog (e.g., polar, undersea, cave)
		3	2	1
Similarity to long-duration expedition astronauts		Similar with respect to age, sex, and education, and possibly cultural diversity	Similar with respect to age and education, but not sex or cultural diversity	Possibly similar with respect to age, but not sex, education or cultural diversity
		3	2	1
Similarity with respect to duration of mission	Over 12 months	6–12 months	1–6 months	Less than 1 month
	4	3	2	1
Similarity to crew size		Small (1 to 8)	Moderately small (9 to 15)	Large (>16)
		3	2	1

*Overall fidelity: High: 10–13 (33 studies); Medium: 7–9 (27 studies); Low 4–6 (9 studies).

Finally, the quality of the evidence for all outcome measures was evaluated using the Grading of Recommendations Assessment, Development and Evaluation (GRADE) methodology, based on consistency, directness, precision, and publication bias. Where appropriate, additional domains were considered using the Cochrane Handbook for Systematic Reviews of Interventions (Higgins and Green, 2008) and criteria taken from Bartone et al. (2018). Quality was categorized as high, medium, or low.

3. Results

3.1. Search results

A total of 3056 publications were initially identified. After screening of titles and abstracts (TI+TB) 561 duplicates were removed, and a further 2258 items were excluded. The remaining 237 full-text articles were assessed for eligibility, which resulted in a further 168 being excluded. Of these: six were not written in French or English; in 15 cases, only the abstract was available; 28 papers were systematic reviews; two studies focused on periods of confinement of less than 15 days; 58 were out of the scope of this review; eight were historical; one focused on space travelers selection; 10 studied interpersonal issues; 13 were run in other extreme environments; seven studied immune function, metabolic and morphologic change, or endocrine response; three validated tools for studying populations in ICE/EUE; three provided insufficient detail; two lacked objective measures; seven were too short (i.e., less than two pages); three contained biases (e.g., methodological shortcomings); one was not found; and one was removed after publication. The final corpus consisted of 69 studies that met the inclusion criteria. Table 3 reported characteristics and results of included studies in this review (Supplementary material).

3.2. Study characteristics

3.2.1. Publication year

Only a few studies were published before 2013 (two in 2005; one in 2007, 2008; and 2009; four in 2010; two in 2011, and two in 2012). From 2010, the number increased, as follows: seven in 2013 and 2014; nine in 2015 and 2016; four in 2017; five in 2018; seven in 2019; six in 2020; three in 2021; one in 2022.

3.2.2. Country

Sixteen individual countries were identified, broken down as follows: the United States (14), Brazil (1), Argentina (2), France (2), Belgium (5), Netherlands (1), United Kingdom (2), Germany (2), Italy (1), Russia (4), Hungary (1), Ukraine (1), the Czech Republic (2), India (4), China (7), and Japan (1). Thirteen other studies were carried out by international teams, and seven were run by Europe collaborations.

3.2.3. Participants

Sample size and crew composition varied. 69 documents reported the number of participants (mean = 35.79). Of these, the activity was broken down as follows: 113 individuals participated in a spaceflight mission (11 studies); 247 participated in a spaceflight simulation (29 studies); 934 spent several months at a polar station (26 studies) or a polar expedition (1 study); and 163 were studied onboard a submarine (2 studies).

Ages ranged from 20 to 60 years (56 studies). In studies of the polar environment, ages ranged from 20 to 60 (20 studies). In 9 spaceflight studies, subjects ranged from 33 to 63. In studies of simulated spaceflight to Mars, participants ranged from 24 to 55 (26 studies). Forty studies reported the gender of participants. Most focused-on men (26), some were mixed (24), and only two investigated women. The followed ethnicities were reported: International (17); European (5), of which the majority were French and Italian crews; Russian (1); Ukrainian (1); Indian (3); Chinese (5); Japanese (1); American (3); and Argentinean (1). All studies report sample size, while others did not report demographic factors such as age (13), gender (17), or ethnicity (32).

3.3. Study quality

Most studies were evaluated as medium (51) or low (10) quality. Only six included a control group. Of these, four were rated as high quality, while the others were downgraded due to missing informations. Overall, eight studies were assessed as high quality.

Only two studies specified the design (i.e., a controlled case study, a prospective study), and none of the others clarified this point. This is understandable as most investigations are case studies, with several biases that are inherent to the environment in which the mission takes place. Some studies did not specify the methodology (12), or list inclusion criteria (32). It should be noted, however, that these studies have the benefit that they were run in an ecological environment.

3.4. Impacts of ICE/EUE

Human impacts of ICE/EUE can be categorized into eight groups of factors: temporal, psychiatric, psychological and health, cognitive, physiological, neurophysiological, sensory, and post-mission. These are analyzed in detail in the following sections. For each category of impact, we have endeavored to describe them by systematically organizing them by environment: space, simulation, polar and submarine environments. This organization has the advantage of highlighting the information gaps (i.e., the environments for which the impact category has not been studied).

3.4.1. Temporal impacts

Steinach et al. (2016) highlight the effect of overwintering time on sleep as a cumulative effect to environment exposure. These effects are particularly worsted during winter, suggesting an additional seasonal aspect to the temporal aspect of the mission. The question of the emergence of a cluster of symptoms around the third quarter of a mission has been discussed for several years. Leon et al. (2011) suggest that it could be related to the harshness of the environment. A study of a polar wintering mission by Décamps and Rosnet (2005) found evidence of a third-quarter phenomenon that was dependent on stress responses (in particular, a significant decrease in the total number of stress responses) and appeared to be consistent with an increase in the number of thymic responses, a decrease in the number of social responses, and a stabilization in the number of somatic responses. However, the same study found no link with occupational reactions. The authors argued that the phenomenon should appear just after the middle of the isolation period, rather than just after the middle of the mission. Also, sleep disturbance, cognitive impairment, and negative affect tend to worsen in the third quarter (Basner et al., 2013; Bhattacharyya et al., 2008; Collet et al., 2015; Folgueira et al., 2019; Sandal et al., 2018; Steinach et al., 2016). Results from other studies are inconclusive. For example, Wang and Wu (2015) found no evidence of an effect on crewmembers' emotional state during a space simulation. Khandelwal et al. (2017) reported similar results for an Antarctic wintering. Individual variability among participants may explain these divergent findings. Environmental factors may also play a role, as the syndrome has not been observed in space and underwater analogs.

3.4.2. Psychiatric impacts

The literature reports symptoms of depression, anxiety, irritability, asthenia, apathy, boredom, decline in initiative, and a decrease in general activity and desire (Basner et al., 2014; Hao et al., 2020; Kanas et al., 2013; Lugg et al., 2005; Nicolas et al., 2021; Palinkas & Suedfeld, 2021; Stuster et al., 2010).

Although no evidence of depression was detected during the Mars 500 simulation, one crewmember reported depressive symptoms in 93% of weeks (Basner et al., 2014). No psychotic disorders seem to have been reported during space missions, notably because of the selection of candidates.

In polar stations, Strewe et al. (2018) investigate the effects of hypoxia. They found higher anxiety level at Neumayer III than at Concordia station, although significance is not met. At the Indian Maitri Antarctic station, Premkumar et al. (2013) report an increase in depression and anxiety, together with increased stress scores during the midwinter compared to summer suggesting a « winter overing » effect. This effect is linked to seasonal effects that are known to be dependent of missions in Antarctica. However, the occurrence of such disorders remains rare. This argument is supported by Tortello et al. (2020), who found that the severity of depressive and anxiety symptoms remained below the criteria for mental disorders throughout a year-long wintering expedition. Moreover, none of the measured scales showed significant variation during this time, indicating stable mood. A recent review by Oluwafemi et al. (2021) assessed the risk of disorders in stressful situations such as ICE/EUE. Although most of the time symptoms did not require psychological support, and were self-limiting, the authors suggest that psychiatric disorders could occur during future long-duration space travel and could challenge the space travelers' ability to accomplish the mission.

No such symptoms were reported both in space (Garrett-Bakelman et al., 2019) and on SSBN board (Brasher et al., 2012; Trousselard et al., 2015).

3.4.3. Psychological and health impacts (i.e., sleep, mood, emotions, stress, somatization)

Extreme environments impose multiple challenges on crews, both in terms of the environment (e.g., extreme temperatures, confinement, isolation) and the number of stressors (e.g., separation from loved ones). Repercussions on the stress level, sleep, and mood of crews are diverse (Basner et al., 2014; Bhattacharyya et al., 2008). Given the duration of the missions, this is a mood related factor (i.e., effect of duration and no specific cause) whereas a particular event during the mission may generate emotions. These questions were mostly examined in analog studies, aiming to minimize the potentially devastating consequences of psychological disorders for the mission. These studies have highlighted the impact of the environment on the psychology of crews (Hao et al., 2020; Kuwabara et al., 2021; Moraes et al., 2020; Nicolas et al., 2021; Nicolas et al., 2022; Palinkas & Suedfeld, 2008; Palinkas & Suedfeld, 2021; Rai & Kaur, 2012; Trousselard et al., 2015).

The Mars 500 mission was an opportunity to run several studies on the mood and sleep of the crew. The findings highlighted a variation in mood over time (Basner et al., 2014; Gemignani et al., 2014; Šolcová et al., 2014; Wang et al., 2014), with the most extreme values reported around day 366 (Wang et al., 2014). In this context, mood may be defined as low intensity, diffuse and relatively enduring affective states without a salient antecedent cause and therefore little conscious cognitive content. In contrast, emotions are more intense, short-lived, and usually have de definite cause and conscious cognitive content (Forgas, 1995; Forgas, 2002). We used inside the review the terms ‘mood’ and ‘emotions’ based on the referencing of the studies mentioned. Although a decrease in positive emotions was observed, there was no change in negative emotions (Šolcová et al., 2014; Yi et al., 2016), while crewmembers tended to evaluate unpleasant stimuli positively (Wang et al., 2014). Several studies report a significant increase in fatigue (Basner et al., 2013; Basner et al., 2015; Wang & Wu, 2015; Zavalko et al., 2013). Fatigue was found to be significantly higher in the first, compared to the fourth quarter, due to a heavier workload, lack of free time, and greater crew autonomy (Wang & Wu, 2015). An earlier study, run during the Mars 105 mission highlighted difficulty in falling asleep, nocturnal awakening, a decrease in delta activity during sleep, and a lack of rapid eye movement sleep (Kovrov et al., 2012). However, these results were not confirmed by other studies (Chen et al., 2016a; Gemignani et al., 2014; Matsangas et al., 2017; Pattyn et al., 2017; Trousselard et al., 2015; Wang & Wu, 2015; Yi et al., 2014).

A report of overwintering at two Chinese Antarctic stations identified different patterns of mood change depending on the station's location using the profile of moods scale (Chen et al., 2016a). Specifically, no statistically significant differences in indicators were identified for winterers at the Great Wall Station (Chen et al., 2016a). Chen et al. (2016b) found evidence of SAD in two subjects at the Chinese polar station, Zhongshan. The latter authors reported a greater number of depressive symptoms, increased appetite (associated with weight gain), fatigue, and decreased sociability. In contrast, at the Zhongshan Station, negative affect (i.e., fatigue, anger, tension, confusion) significantly increased. Fatigue increased until mid-winter, and peaked at the end of the season, while the other measured variables peaked in mid-winter. A relation between emotions and fatigue was found by (Chen et al., 2016a), who observed that the most severe environmental characteristics were associated with the worst effects. Findings from studies at NASA's Human Exploration Space Analog (HERA) facility are mixed (Weber et al., 2019; Nasrini et al., 2020). In general, crewmembers remain healthy, with mostly positive emotions and good sleep quality – performance degradation appears to be mainly caused by sleep deprivation. However, the average duration of these missions is one month, leaving doubts about their similarity to future long-duration trips in space.

The literature highlights high levels of stress in ICE/EUE, whether during space missions (Barger et al., 2014), simulations of future long-duration space missions (Basner et al., 2014; Jacubowski et al., 2015; Wang et al., 2014; Yi et al., 2014; Yuan et al., 2019), or a stay in a polar environment (Binsted et al., 2010; Moraes, 2020; Nicolas et al., 2015; Nicolas et al., 2021; Nicolas et al., 2022), with levels peaking at approximately day 500 (Wang et al., 2014; Yi et al., 2014). Social stress appears to have most impact (Nicolas & Gushin, 2014; Nicolas et al., 2015).

Concerning health, most studies highlighted sleep and somatization concerns. The majority of studies on sleep were run during a polar winter. Identified disorders include desynchronization of circadian rhythms, delayed chronotypes, insomnia, sleep latency, decrease in slow-wave sleep, periodic awakening, deeper or shallower sleep and fewer dreams. These effects are ascribed to environmental conditions (e.g., photoperiodicity, cold, altitude), and lead to an increase in subjective fatigue (Bhattacharyya et al., 2008; Binsted et al., 2010; Chen et al., 2016b; Collet et al., 2015; Folgueira et al., 2019; Gríofa et al., 2011; Kuwabara et al., 2021; Mairesse et al., 2019; Nicolas et al., 2022; Palinkas & Suedfeld, 2008; Palinkas & Suedfeld, 2021; Pattyn et al., 2017; Sandal et al., 2008; Steinach et al., 2016). Premkumar et al. (2013) investigated sleep both in summer and winter at Maitri station. In five subjects, they found daytime sleepiness during summer, and two of them during midwinter. When exploring the sleep logs, a seasonal difference was highlighted (i.e., decrements in sleep latency, early morning awakenings, sleep recovery, increased sleep time during wintering) in 25% of subjects. Nevertheless, scientists reported a decreased sleep length in summer compared to technical support team in winter. Authors noted that this result was attributed to an increase in napping due to lack of work in winter. Also, a gender difference was found in polar regions leading to sleep quality decrements for woman (Schneider et al., 2016).

Trousselard et al. (2015) did not find a significant effect on sleep, sleepiness, and confusion between days 21 and 51 of a nuclear submarine patrol.

The literature reports several somatic symptoms, such as gastrointestinal complaints (i.e., heartburn, gastric discomfort, gastritis and upset stomach, flatulence, diarrhea, and constipation), digestive disorders, dyspepsia, rheumatic pain, dental pain, headaches, loss of appetite, weight loss, cardiac extrasystoles, and heightened sensitivity to physical and social stimuli (Kanas et al., 2013; Nicolas et al., 2022; Palinkas & Suedfeld, 2008; Yuan et al., 2019). These symptoms appear to be closely associated with stress, without being systematic (Yuan et al., 2019). Although one study found a significant correlation between weight-related phenotypes and psychological factors (Hao et al., 2020), other data do not support this idea. In a four-month study of the Mars 105 crew, (Nicolas & Gushin, 2014) found that exposure to an extreme environment did not systematically lead to stress overload or altered psychological states. Similarly, in a study of Antarctic wintering, Strewe et al. (2018) found a distinct modulating effect on the stress response that was not associated with psychological stress. Specifically, at both Concordia (high altitude) and Neumayer III (sea level), stress measures did not significantly change throughout the deployment. However, although overall stress measures did not reach significance, levels were higher at Neumayer III than at Concordia.

Over-commitment and rank lead to increase the level of stress for submariners (Brasher et al., 2012).

Overall, the psychological impact of the mission seems to be related to the length of time spent in the environment and its severity, although here again, there is great inter-individual variability. Most studies identify changes from the first weeks of the mission and note that the stress induced by the environment could lead to subsequent maladjustment (Nicolas et al., 2015).

3.4.4. Cognitive impacts

In space, the literature reports a decrease in cognitive capacities (i.e., under high cognitive load), productivity, vigilance, and collective and individual efficiency, together with an increase in the number of errors (Kanas et al., 2013; Palinkas & Suedfeld, 2021; Patel et al., 2020; Pattyn et al., 2005; Roberts et al., 2019). Cognitive impairment was also reported in the review by Flynn (2005). Effects could be due to microgravity, radiation, stress, or even the tools used (Flynn, 2005; Nasrini et al., 2020; Oluwafemi et al., 2021).

Executive functions seem to be particularly impacted under the non-ecological gravity experienced in space. Studies report a decrease in problem-solving ability, memory (working, short-term, and spatial), learning, attention, and reaction times (Roberts et al., 2019; Moore et al., 2019; Pattyn et al., 2005). These changes appear to be related to a sleep deficit, and the circadian desynchronization problems faced by space travelers, along with stressors inherent in the environment, notably monotony (Kanas et al., 2013; Nasrini et al., 2020; Palinkas & Suedfeld, 2021). Specific white matter regions such as the bilateral optic radiations and the splenium of the corpus callosum were associated with altered reaction time (Roberts et al., 2019).

Many cognitive functions are critical to the mission's success and crew safety. During a 340-day space mission, accuracy and speed scores were found to decrease between the beginning and the end of the flight (Garrett-Bakelman et al., 2019). Surprisingly, cognitive speed was higher in all domains at the beginning of the flight. Other authors underline that it is difficult to evaluate the real impact of the space environment on the cognition of space travelers (Flynn, 2005; Oluwafemi et al., 2021; Roberts et al., 2019). Although some space travelers have reported a subjective decline in cognitive performance, the review by Flynn (2005) highlighted that only minor changes could be recorded using objective measures (i.e., increased test response time, reduced accuracy of responses, poorer performance when tracking two tasks, altered visual-spatial recognition ability). In particular, he cites a study of long-duration flights, where these impairments were most problematic during the first 20 days, but then resolved during the mission.

Analog studies have also observed an impact of the environment on cognitive function, whether in polar environments (Palinkas & Suedfeld, 2008; Premkumar et al., 2013; Nicolas et al., 2015; John Paul et al., 2010) or space simulations (Binsted et al., 2010; Cohen et al., 2016; Flynn-Evans et al., 2020; Yi et al., 2016). A recent study at the HERA facility (Nasrini et al., 2020) highlighted a significant impact on psychomotor alertness in terms of speed and accuracy, and cognitive output. Weber et al. (2019) studied a 30-day isolation at the HERA facility and found that it had no significant effect on cortical activity or cognition, despite an increase in cortisol. Other studies have shown no negative impact on cognitive activity while wintering in Antarctica (Barkaszi et al., 2016; Folgueira et al., 2019; Gríofa et al., 2011; Palinkas et al., 2007); or in a 105-day simulation (Gemignani et al., 2014). John Paul et al. (2010) studied the Indian Maitri station in Antartica and observed a positive effect on recognition memory and learning, and a neutral effect on short-term memory during a one-year stay. The latter authors concluded that in extreme situations, individuals can manage their stress and remain cognitively efficient.

Finally, it should be noted that no studies have been run onboard SSBN.

3.4.5. Physiological impacts

Most studies examine Heart Rate Variability (HRV) and cardiovascular and breathing adaptation. In a study that investigated the impact of isolation and confinement on cardiovascular and brain function, Garrett-Bakelman et al. (2019) showed that, during a 340-day space mission, the environment increased internal jugular vein cross-sectional area, frontal tissue thickness, cardiac filling, stroke volume, and cardiac output. The latter authors also found a decrease in these changes during a long-duration space flight on the ISS.

Several studies have highlighted that the Mars 105 mission, which laid the foundations for the Mars 500 mission, was not as stressful as the latter. In particular, the literature has identified the effects of the two missions on HRV. Studies carried out during the Mars 500 mission used HRV to assess the functional status of a human being in an extreme environment (Bersenev et al., 2013; Šolcová & Vinokhodova, 2013). A 2013 evaluation of the vegetative regulation of blood circulation and individual health risks during the 520-day Mars 500 mission reported changes in HRV parameters (Bersenev et al., 2013). The most noticeable changes occurred during the simulation of the return trip: a decrease in heart rate; an increase in sympathetic regulation; an increase in parasympathetic regulation; and sympathetic and neurohumoral regulation. On waking, the following observations were recorded: greater amplitude oscillations, mainly at high and low frequencies; an increase in HRV; and a decrease in heart rate that contrasted with a decrease in the high frequency component during sleep (Vigo et al., 2013), along with increased parasympathetic activity (Vigo et al., 2012; Vigo et al., 2013). These changes seemed to be more pronounced during the second month of isolation (Vigo et al., 2012).

In their study of the Mars 105 mission, Wan et al. (2011) found that the autonomic nervous system was altered through a decrease in blood pressure regulation. A reduced cardiovascular response to mental stress was particularly evident during the first month of confinement but did not persist after leaving. Similarly, confinement did not affect the cardiovascular response to slow-paced breathing. The Chinese Controlled Ecological Life Support System experiment (Yuan et al., 2019) found that individuals' morning heart rate and blood pressure remained normal, and HRV frequency markers (Low Frequency, LF and High Frequency, HF) along with baroreflex sensitivity, were not pathologically altered. Furthermore, carotid intima-media thickness and masseter tone increased, and endothelium- and paravertebral muscle-dependent vasodilation decreased. A space simulation onboard the Lunar Palace (Hao et al., 2020) examined the correlation between blood pressure and heart rate, and psychological changes. The study found that the lower the morning diastolic blood pressure, the more anxious individuals were. The lower the bedtime diastolic blood pressure, the more prone they were to fatigue-inertia, obsessive-compulsiveness, anxiety, and phobic anxiety. Finally, the lower the bedtime heart rate, the more anxious they were.

Results seem more mixed for polar stations. Moraes et al. (2020) evaluated the physiological effects of an Antarctic expedition, consisting of a 26-day trip onboard a ship, followed by a 24-day summer camp in the Antarctic field. The study found changes in the cardiac autonomic regulation of HRV parameters during the trip onboard the ship. Biphasic changes were found in the Root Mean Square of Successive Differences (RMSSD) and the Proportion of number of pairs of successive NN intervals that differ by more than 50 ms divided by the total number of NN intervals (pNN50). Parasympathetic activity, assessed from the HF band, decreased on day 16, then moderately increased, before returning to pre-mission values. No differences were observed between initial and final measurements. Fluctuation in the HF band, and the unchanged LF band resulted in a biphasic response of the LF/HF ratio. In contrast, no changes were observed for resting heart rate, or any of the HRV parameters during the summer camp. Similarly, a 2019 study by Folgueira et al. found no significant changes in blood pressure during wintering at the Antarctic Belgrano II station, while Gríofa et al. (2011) found no significant cardiopulmonary changes during a 37-day polar wintering.

3.4.6. Neurophysiological impacts

Several studies highlight neurophysiological responses during long-duration space missions. There appear to be major structural changes at the cerebral level, including a redistribution of cerebrospinal fluid, decreased ventricular volume, and a generalized decrease in gray matter volume (Lee et al., 2019; Stahn et al. , 2019; Roberts et al., 2019). Roberts et al. (2019) have shown significant global and local (i.e., crowding of the brain parenchyma, displacement of the brain parenchyma as the ventricles dilate) changes in brain structure after a space mission on board the ISS. Lee et al. (2019) reported a shift of cerebral spinal fluid upwards in the brain after all long (but not short) space flights, along with a narrowing of the cerebral spinal fluid spaces in the vertex after all long flights (but in only one crew member after short flights). Combined changes are observed in somatosensory, visual, vestibular, and cardiovascular function (Demertzi et al., 2016; Kanas et al., 2013; Liu et al., 2015; Moore et al., 2019; Verheyden et al., 2009). Liu et al. (2015) report that microgravity leads to change in blood circulation, which becomes more efficient due to the redistribution of cephalic blood. Alterations in cerebellar and motor connectivity, as well as a decrease in vestibular connectivity, particularly in the right insula, have been observed (Demertzi et al., 2016). Sensory conflicts between visual and tactile inputs, and the vestibular organs can lead to a syndrome of adaptation to space (Kanas et al., 2013; Moore et al., 2019; Van Ombergen et al., 2017).

During the Mars 500 mission, Yi et al. (2016) examined the impact of chronic exposure to isolation and confinement on brain cortical activity and identified a reduction. Similar results were found in a study of neural activity during 120 days of isolation in a spatially confined, space-analog environment (Weber et al., 2020). Jacubowski et al. (2015) reached similar conclusions. In particular, the authors found that a decrease in neurotrophicity, assessed by Blood brain Derived Neurotrophic Factor (BDNF) concentrations, was linked to a decrease in dentate gyrus volume, the latter being associated with decreased cognitive performance in spatial processing and selective attention tests.

In the polar environment, Stahn et al. (2019) evaluated the effects of physical and social deprivation on the hippocampus, based on MRI scans of eight members of a polar expedition. Their results highlighted a reduction in hippocampal volume in the dentate gyrus compared to controls. A significant reduction in gray matter volume in the left parahippocampal gyrus and left orbitofrontal cortex was also reported. Finally, a decrease in cortisol concentration is reported to be consistent with adaptation to confinement during a summer camp in Antarctica (Moraes et al., 2020).

Any results are reported on SSBN patrol.

3.4.7. Sensory impacts

In space, sensory input is limited, and space travelers’ sensory responses are altered. The neurovestibular system is one of the first to be affected during spaceflight (Kim et al., 2018b).

3.4.8. Vestibular system

Demertzi et al. (2016) reported the results of a 44-year-old cosmonaut who spent 169 days on board the ISS. Alterations were observed in the vestibular and motor regions. The observed dysfunctions were correlated with vestibular ataxia and reduced motor control abilities. Results from space missions show significant decreases in postural stability, oculomotor control, eye-hand coordination, eye-neck coordination, and proprioception during the flight (Bloomberg et al., 2015a; Bloomberg et al., 2015b; Wood et al., 2015). These effects become more pronounced as the mission length increases (Roberts et al., 2019). Overall, there are several acute and chronic sensorimotor events during space flight that may affect operational proficiency (Moore et al., 2019). These include space motion sickness, spatial disorientation, proprioception changes, or the ability to track visual targets. Also, Roberts et al. (2019) highlighted an association between decreased postural control recorded after the space mission and changes of the left caudate nucleus in case of a task requiring dynamic control of postural balance. More specifically, the decrease in motor function performance was predicted by structural change of the left caudate nucleus and the right lower extremity primary motor area/midcingulate. These events are driven by vestibular modifications.

A study run in the context of the NASA Extreme Environment Mission Operations project (NEEMO) in the underwater Aquarius module (Kim et al., 2018b) found that measurements of upper body balance and gait regularity during open and closed eye tandem walking revealed anomalies, due to changes in sensorimotor performance during the 15-day mission. The variability and amplitude of gait regularity for left-handed steps, along with trunk displacement, were correlated with the duration of time crew members spent in the habitat. Although gait regularity for right-handed steps was not significantly different, wide variability in performance was noted.

3.4.9. Spatial navigation system

Sensors used in spatial navigation could be impaired during long-duration spaceflight (Moore et al., 2019; Wood et al., 2015).

Perceptual distortion has been reported in space travelers onboard the ISS (Wood et al., 2015) and during the Mars 500 simulation mission (Sikl & Simeček, 2014). Similarly, although crew members' 3D perception was not found to change significantly during the Mars 500 mission (Sikl & Simeček, 2014), the relative length of 2D lines was consistently misperceived. Parallel line lengths were generally judged more accurately than perpendicular line lengths, and the magnitude of under and overestimations was lower among the crew than in a control group.

No such results were reported in other analog environments.

3.4.10. Vision system

The literature has, for many years, highlighted the cerebrospinal displacement of fluids during stays in space. This phenomenon has major impacts on the body, notably the visual function (Lee et al., 2018; Strangman et al., 2014). This shift results in an elevated intracranial pressure that causes visual alterations. These changes occur during a timeframe of three weeks to three months after arrival in the space environment (Demontis et al., 2017). Radiation exposure can also damage vision. An innovative study of twins, one in space, the other on Earth, found that a stay of 340 days led to ocular modifications in the astronaut that were not present in their twin on Earth (Garrett-Bakelman et al., 2019). More specifically, the authors identified an increase in the thickness of the sub foveal choroid, and the total thickness of the peripapillary retina (i.e., retinal edema). Moreover, the severity of the astronaut's choroidal folds, present before the mission, increased during spaceflight.

In contrast, an ophthalmological study of the first trans-Antarctic winter expedition (Stahl et al., 2018), which examined explorers who overwintered in Antarctica, did not identify any pathological changes in visual acuity, contrast sensitivity, color vision, auto-refraction, subjective refraction, retinal examination, retinal autofluorescence and retinal thickness, or intraocular pressure.

No such results were reported in other analog environments.

3.4.11. Gustatory system

Gustatory alterations were reported during a 15-day confinement onboard an analog reproduction of the Martian desert (Rai & Kaur, 2012). In the latter study, subjects completed both mental and physical tasks, and tastes were found to be more pronounced after physical than mental tasks. After mental tasks, decreases were found for bitter, sour, and sweet tastes with respect to peak intensity, duration of aftertaste, and total amount of taste (i.e., summation every 5 s). After physical tasks, peak intensity changed, as did the duration of aftertaste, and total amount of aftertaste for bitter and sweet taste, while sour tended to decrease. The authors also reported a relationship between the time-averaged intensity of sweetness, bitterness and sourness, and stress (measured as cortisol levels).

No such results were reported in analog environments.

3.4.12. Post-mission impacts

Return to Earth is a particularly stressful event. Gravity, and readjustment to life in society make it one of the greatest physiological challenges of spaceflight. In the period immediately following landing, stress manifests as cardiovascular and musculoskeletal problems, and inflammatory reactions. Liu et al. (2015) reported a lack of rhythmicity of body trunk 4–6 days after the end of the spaceflight. Impacts on mood and performance include drug addiction, major depressive symptoms, and anxiety that may require psychotherapy and psychoactive medication (Kanas et al., 2013). Coming home after a long period away can be difficult for families; jealousy and marital problems can end in divorce (Kanas et al., 2013).

Garrett-Bakelman et al. (2019) observed a decline in the cognitive functions (speed, accuracy) of an astronaut who spent 340 days in space, compared to their twin who remained on Earth. This decline persisted for six months after the return. However, Moore et al. (2019) highlighted that fatigue alone is not responsible for the decrease in performance. (Nicolas & Gushin, 2014) reported lowest levels of perceived stress upon return from the Mars 105 simulation, while fatigue increased. Stahn et al. (2019) also concluded that BDNF levels had not recovered one and a half months after the end of a polar expedition, suggesting an impact on key cognitive functions. Recovery from ocular changes that occur during a space mission remains a concern. While recovery is possible in some cases (e.g., choroidal congestion), others persist or worsen. Choroidal folds have been found to remain following a stay in space (Garrett-Bakelman et al., 2019).

Nicolas et al. (2022) highlights that recovery was inversely proportional to the severity of polar environment. While no decrease was observed at Kerguelen station, recovery responses decreased at Dumont d'Urville.

Six months after leaving the 520-day Mars 500 simulation, crew members participated in a parabolic flight campaign during which they were subjected to acute stress (Yi et al., 2015). Cortisol levels increased compared to the control group, indicating marked chronic stress.

Postural stability and walking speed are deeply impacted during the first twelve hours following the return from a space mission, and several weeks after landing, space travelers continue to have difficulty standing when performing dynamic head tilts (Wood et al., 2015). Anatomical changes and visual problems have been found to persist for several months, or even years after the return to Earth (Strangman et al., 2014). Furthermore, the absence of the usual gravitational force in space has been shown to affect various brain mechanisms, including the efficiency of cognitive and perceptual-motor skills (Kanas et al., 2013). Once out of the environment, the NEEMO analog crew had not recovered their pre-mission sensorimotor performance. Improvements to postural stability after landing can be divided into two phases: an initial rapid improvement, followed by a gradual recovery.

No post-mission factors are reported in the reviewed studies of submariners. Overall, the reviewed studies confirm, and provide some additional insight into the role of recovery and stress in adaptation to ICE/EUE. Finally, an important insight that emerges from these studies is the role of inter-individual differences among crew members. Further investigations of adaptation mechanisms are needed to better-understand how individuals cope with extreme conditions.

3.5. Psychological mechanisms and adaptation to ICE/EUE

The literature refers to several types of adaptation, mainly drawing upon the coping framework (Lazarus & Folkman, 1984; Lazarus & Folkman, 1985; Lazarus, 1986). The selected studies highlight the importance of different coping strategies for understanding positive adaptability. Most focus on space simulation and polar environments, while none address submarine patrols.

3.5.1. Coping and defense strategies

A review by Leon et al. (2011) argues that problem-solving strategies are an effective way to overcome decreased motivation, especially towards the middle of the mission. However, the authors also highlight the importance of engaging in emotion-oriented strategies, as they appear to be an effective way to cope with stressful situations via emotional regulation and sharing one's emotional state. As early as the Mars 105 simulation, it was concluded that task-oriented adaptation was associated with positive adaptation, while withdrawal or disengagement was associated with depression and poor adaptation (Palinkas & Suedfeld, 2021). Nicolas et al., (2013, 2014) provided further insights into crew adaptation. They found a link between defense mechanisms (i.e., mature defenses, intermediate defenses, immature defenses), coping (i.e., task-oriented coping, disengagement-oriented coping), and emotional state (i.e., positive emotions, depressive symptoms) (Nicolas et al., 2013). Tortello et al. (2021) found similar results among Antarctic winterers, notably a relationship between task-oriented coping and defense mechanisms (i.e., immature, mature). Nicolas et al. (2015) also found a link between stress, mature defenses, and recovery during a one-year wintering at the Concordia station. Individuals who used mature defense mechanisms appeared to be better-able to adapt to the stressful environment, and their recovery was efficient (Tortello et al., 2021; Van Ombergen, 2021), regardless of season or isolation (Tortello et al., 2021). Recently, Nicolas et al., 2021, Nicolas et al., 2022 show that both perceived control and environmental mastery are involved in adaptation processes. They found that level of perceived control is associated with emotional, social, and physical adaptation at both Concordia and Amsterdam station, and that this indicator predict emotional adaptation for winterers at Concordia (Nicolas et al., 2021). Also, they reported that the level of environmental mastery correlates with the evolution of success (Nicolas et al., 2022). Those with a low level of environmental mastery experienced more success through the wintering instead of those with high levels remains stable (Nicolas et al., 2022). Moreover, coping appears to be a function of gender, with men using more avoidant coping, and females using more active strategies (Binsted et al., 2010). It seems that women are better-able to cope with stressors and, thus, adapt to ICE/EUE (Palinkas & Suedfeld, 2021).

3.5.2. Behavioral strategies

Other authors note different coping strategies in extreme environments. These include redirecting negative affect to the control center rather than to crew members (i.e., displacement) (Kanas et al., 2013), self-sufficiency and autonomy (Kanas et al., 2013), and strategies derived from the individual's personality (Bersenev et al., 2013; Wang et al., 2014), functions assigned during the mission (Bersenev et al., 2013; Palinkas & Suedfeld, 2008), and resilience (Sandal et al., 2018). The role of interpersonal relationships in adaptation is also highlighted (Kuwabara et al., 2021; Tortello et al., 2021). A wintering at the Japanese Antarctic station revealed four types of coping strategies: the use of instrumental social support, denial, acceptance, and planning (Kuwabara et al., 2021). The results of the Baum test on 172 Japanese winterers (i.e., only 11 women were in the sample) over a period of 5 years at the Syowa polar station showed two types of behavior to cope with the extreme environment. Some of them clung to the memories of the life they had before and tried to copy this old life to the new one in Antarctica. Others adjusted by adopting a new way of life. These are both types of behaviors that allow for maintaining mental states during the mission. However, having a flexible adaptive behavior, as highlighted by the second case, implies having sufficient resources to fit with the demands of the new environment. Thus, this type of behavioral coping allows for quality adaptation.

3.5.3. Impacts of the timeline on strategies

Some authors suggest that coping is nonlinear over time. The mission itself has a psycho-physiological impact that evolves as it progresses. Many note that coping occurs in stages (Demertzi et al., 2016 ; Kanas et al., 2013 ; Khandelwal et al., 2017 ; Moiseyenko et al., 2016 ; Wang et al., 2014). Psychological and cognitive changes seem to reflect strategies that individuals use to cope with the environment. These changes evolve during the mission (Kanas et al., 2013; Moiseyenko et al., 2016; Palinkas & Suedfeld, 2021; Tortello et al., 2021; Demertzi et al., 2016; Wang et al., 2014), with a decrease by the third quarter, regardless of the environment (i.e., space or analogs) (Kanas et al., 2013; Tortello et al., 2021; Wang et al., 2014). Gushin et al. (1993) highlighted an accommodation over time in space travelers' adaptation. The authors developed a four-stage model of emotional change during a space flight: (1) psychological and physical discomfort at the beginning of the flight; (2) six weeks into the flight, psychological and physical adaptation began, but the space travelers were not yet impacted by the isolation and confinement; (3) between the sixth and twelfth weeks, the space travelers became less stable; (4) a feeling of euphoria developed during the last phase.

Adaptation has been investigated in analogs. Studies have identified three stages, with minimal effectiveness at the beginning, some increase in effectiveness in the middle, and a decrease at the end of the mission (Khandelwal et al., 2017; Moiseyenko et al., 2016; Nicolas et al., 2013). A specific pattern has been noted in the polar environment, namely an acute phase of adaptation, functional stress, relative stabilization, and depression (Moiseyenko et al., 2016). Khandelwal et al. (2017) found that externalized psychological responses peaked in mid-winter, anxiety and insomnia peaked during the coldest period, and cognition was at its poorest during the last phase of an Antarctic wintering. More recently, a new type of adaptation has emerged during wintering in Antarctica – polar wintering (Palinkas & Suedfeld, 2021; Sandal et al., 2018). Individuals appear to enter a state of psychological hibernation as an adaptation to stress, which takes the form of a depletion of resources as the cold period approaches, and the reconstitution of resources in the second half of the stay. This strategy seems, therefore, to be influenced by environmental conditions, and involves a long period of isolation and confinement.

3.5.4. Salutogenic strategies

Other authors compare coping to salutogenic phenomena. The latter term is derived from positive psychology, which supports learning to cope with stressful situations. The term salutogenic, developed by Antonovsky (Antonovsky, 1987), proposes that under certain circumstances, stress does not only have harmful, but also beneficial consequences for health, notably because humans like to engage in flow experiences (Csikszentmihalyi, 2000). Salutogenic appears to be associated with the ability of individuals to overcome the stressors inherent in these environments. Extreme environments can have long-term beneficial effects throughout life. Outcomes include successful stress management, increased strength, better relationships with others, greater autonomy, improved health, personal growth, greater self-confidence, greater belief in human values, and a sense of meaning in life (Palinkas & Suedfeld, 2008; Palinkas & Suedfeld, 2021; Nicolas et al., 2022).

Others go so far as to suggest a combination of psychological, emotional, and cognitive adaptation (Nicolas et al., 2013; Nicolas et al., 2015; Šolcová et al., 2014). It should be emphasized that negative emotions never reached a critical stage during the Mars 500 mission (Nicolas et al., 2013). A study by Šolcová et al. (2014) of the Mars 500 crew suggests that during the simulation, crew members changed how they felt, and regulated their emotions. Each individual favored a different regulation strategy. Three participants preferred to express their emotions as they felt them, while two others preferred to hide their emotions. Crew members preferred to suppress and neutralize their negative emotions, and only openly expressed positively valanced emotions. The authors suggest that changes in the expression of positive and negative emotions are a manifestation of the individual's experience in the ICE/EUE and, thus, a sign of adaptation (Nicolas et al., 2013; Šolcová et al., 2014). Furthermore, Yuan et al. (2019) highlighted an increase of emotional adaptation of the crew towards the mission. In this context, Solcova et al. (2013) showed that the individuals who are best adapted to a 520-day mission should be those with a higher level of stress resistance, and a greater capacity to self-regulate their emotional state. Individual adaptation in ICE/EUE thus appears to be a multifactorial, flexible, and real process. However, understanding psychological strategies for positive adaptation remains a challenge for longer missions, where the data are insufficient to draw any conclusions.

3.6. ICE/EUE and preparing for future long-duration space missions

Table 4 summarizes the characteristics of the space and analogs environment studied in the reviewed corpus.

Table 4

Characteristics of the included studies

General information				Study characteristics		Participants characteristics				Intervention and settings		Outcome data/results	
Title	Author	Year	Country of origin	Objectives	Study inclusion/exclusion criteria	Age	Gender	Race/ethnicity	Number of participants	Method	Measures	Results study analysis	Limits
520-d Isolation and confinement simulating a flight to Mars reveals heightened immune responses and alterations of leukocyte phenotype	Yi B, Rykova M, Feuerecker M, Jäger B, Ladinig C, Basner M, Hörl M, Matzel S, Kaufmann I, Strewe C, Nichiporuk I, Vassilieva G, Rinas K, Baatout S, Schelling G, Thiel M, Dinges DF, Morukov B,	2014	Europe & USA	Evaluate how antiviral immune response will get 2014 affected as a function of stress response	Medical control and preselection	27 – 38 years	Males	3 Russians, 2 Europeans & 1 Chinese	6	Several questionnaires were collected once a week. On this occasion, morning and evening they indicated their current state on 100 mm visual analog scales (VAS). The POMS-SD was measured only in the morning. These measurements were also taken on three consecutive days for each of the six participants during the 11- to 17-day period before the start of the simulation. Participants' saliva was also collected immediately after waking up (post-sampling tooth brushing. BDC samples were collected 7 days before the start of isolation. At the same times as blood collection, participants also collected their saliva samples in the evening before dinner.	Salivary cortisol	Results found levated cortisol levels and a lower activity during this period of confinement. They were no signs of elevation in total mood disturbance	N/A

	Choukèr A									Salivary cortisol was quantified using an automated immunological system based on the principle of electrochemiluminescence			
A Longitudinal Assessment of Psychological Adaptation During a Winter-over in Antarctica	Décamps G, Rosnet E	2005	France	Examine the manifestations of the third-quarter phenomenon by analyzing the data collected with an observation grid completed by the mission's doctor	N/A	21 – 59 years (mean age 29.7)	N/A	N/A	27	The method requires the use of a 59-item observation grid. The grid lists the stress reactions that may be presented during the course of the winter-over. These reactions correspond to the physical and psychological symptoms that have already been observed or reported during previous studies of psychological adaptation in isolated and confined environments conducted until 1996. The 59 stress reactions are divided into the four categories of the classification proposed by Cazes et al. (1980): the thymic reactions (Category V1, 19 items), the social reactions (Category V2, 13 items), the somatic reactions (Category V3, 17 items), and the	Observation grid, total number of stress reactions presented by the winterers and observed by the doctor	Results highlight a third-quarter phenomenon through an increase of the number of thymic reactions (V1), a decrease of the number of social reactions (V2), and a stabilization of the number of somatic reactions (V3). No significant variation of the number of occupational reactions (V4) were	Small sample size, doctors' perception of the winter-over may influence the data collection, winterers could probably try to hide their weaknesses at the beginning of the stay

occupational reactions (Category V4, 10 items). Each week, the doctor noted the presence or the absence of each of the stress reactions for each of the winterers. The winter-over was divided into several periods. The first 10 weeks (1 to 10) of observation corresponded to the summer campaign (SC). The 40 following weeks of observation corresponded to the isolation period of the winter-over. These 40 weeks were divided into four 10-week periods: Weeks 11 to 20 (Period A), 21 to 30 (Period B), 31 to 40 (Period C), and 41 to 50 (Period D). The summer campaign was not taken into account for the study of the third-quarter phenomenon. Consequently, the middle of the isolation period corresponded to the end of Period B and the beginning of Period C	observed between the different periods. No link between the third-quarter phenomenon and the occupational reactions (V4) was established. The third-quarter phenomenon appears just after the middle of the isolation period

Adaptation of heart rate and blood pressure to short and long duration space missions	Verheyden B, Liu J, Beckers F, Aubert AE	2009	Belgium	Evaluate HR and arterial BP	Astronaut selection	40 – 52 years (44 ± 5)	N/A	N/A	6	N/A	ECG, finger arterial blood pressure, brachial arterial blood pressure	Spaceflight do not influence heart rate and blood pressure compared to the supine pre-flight values. Also, all astronauts recoved postflight.	Workload between missions, quantity and quality of sleep, fluid intake and nutrition not controled, others scientific protocols in flight not considered
Affective, Social, and Cognitive Outcomes During a 1-Year Wintering in Concordia	Nicolas M, Suedfeld P, Weiss K, Gaudino M	2015	International	Investigate time patterns and the relationships between perceived stress, recovery, control, attention lapses, and defense mechanisms (DM) during a 12-month wintering in Concordia polar station with an	N/A	21 – 58 years (38.14 ± 11.90)	13 men and 1 female	8 French & 6 Italians	14	During the winter, questionnaires were sent to each volunteer via the Internet at scheduled times. The first (baseline) administration of the psychological measures (ICE 1) occurred within the first day of the deployment. Other administrations occurred throughout the wintering deployment at +3 months (ICE 2), +5 months (ICE 3), +6 months (ICE 4), +8 months (ICE 5), +10 months (ICE 6), and +12 months (ICE 7)	Recovery-Stress Questionnaire (RESTQ-48), Perceived Stress and Control and Mastery Scales, Defense Style Questionnaire (DSQ-40), Mindful Attention Awareness Scale (MAAS)	Total stress showed significant variations during the wintering, mainly in social relations. None of the changes in the recovery dimensions reached statistical significance. Correlation	Small sample size, which precludes generalizations and deeper correlational analyses

				international crew									al analyses between stress-recovery states, defense mechanisms, symptoms of depression, and lapses of attention-concentration indicated several significant relationships. Study highlights the importance of perceived control in recovery	
Alterations in the heart rate and activity rhythms of three orbital astronauts on a space mission	Liu Z, Wan Y, Zhang L, Tian Y, Lv K, Li Y, Wang C, Chen X, Chen S, Guo J	2015	China	Investigate alterations in the diurnal rhythms of activity and heart rate of Chinese astronauts on a space mission	Astronaut selection	33–49 years	2 males, 1 female	N/A	N/A	N/A		Recording time, HR, actimetry, recording frequency	Spaceflight influence heart physiology and function, decreased motion adaptation and diurnal	N/A

												activity rhythms.	
Altitude and Seasonality Impact on Sleep in Antarctica	Collet G, Mairesse O, Cortoos A, Tellez HF, Neyt X, Peigneux P, Macdonald-Nethercott E, Ducrot YM, Pattyn N	2015	Belgium	Investigate how sleep is affected in Antarctica both by a hypobaric, hypoxic environment and by constant daylight or night	N/A	36 ± 9.8 years (Concordia), 26.5 ± 6.1 years (Dumont d'Urville)	Males (Concordia), 13 men and 5 females (Dumont d'Urville)	N/A	21 (8 Concordia, 13 Dumont d'Urville)	Actigraphy data were collected during one session of 24h at both Dumont d'Urville and Concordia during the summer and winter periods, in epochs of 1-min bins. It was supposed to occur 2 to 3 nights. However, only one night was valid across all subjects	Day-time actigraphic parameters: (1) time spent at work (TSWd, min); (2) energy expenditure (EEd, J), and(3) the number of walking steps (NSd, absolute number). Nighttime parameters: (1) time in bed (TIB, min); (2) total sleep time (TST, min); (3) sleep onset latency (SOL, min); (4) sleep efficiency (SE, %); (5) energy expenditure during the night (EEn,	Study highlight poor sleep efficiency both during winter and summer. There were no significant interactions between location and seasonality	Mixed group, different age distribution and small sample size, and evaluation of sleep through actigraphic measurements instead of polysomnography

J); (6) fragmentation (Fr, number); and (7) wake after sleep onset (WASO, min)

Antarctica challenges the new horizons in predictive, preventive, personalized medicine: preliminary results and attractive hypotheses for multi-disciplinary prospective studies in the Ukrainian « Akademik Vernadsky » station	Moiseyenko YV, Sukhorukov VI, Pyshnov GY, Mankovska IM, Rozova KV, Miroshnychenko OA, Kovalevska OE, Madjar SA, Bubnov RV, Gorbach AO, Danylenko KM, Moiseyenko OI	2016	Ukraine	Analyze and discuss the retrospective data of long-term monitoring and observations in Ukrainian Antarctica station « Akademik Vernadsky » and analyze the biomedical information with regard to extreme environmental factors to determine the mechanisms of « pre-pathology » process that allow to develop pathogenetically based pro-active prevention methods for a number of common diseases which may be promising	Complex medical examination including clinical diagnostics, c oncentrations of microelements in blood serum, functional diagnosis, psychological and psycho-physiological examination, genetic diagnosis, morpho-functional examination of the vision	20–60 years (mean age 37.0 years)	Males	Ukrainian	200	Medical and biological studies have been performed with the participation of all 20 Ukrainian wintering expeditions. Extensive medical examinations were carried out before the expedition, during the selection of candidates, and after returning, and particular functions were monitored during the entire stay in Antarctica. Daily, medical doctor recorded the lood pressure, pulse, temperature; monthly electrocardiography, electroencephalography, spirography, rhythmocardiography; quarterly psychological testing, clinical and biochemical blood tests, densitometry	Electrocardiography (ECG), electroencephaolography (EEG), spirometry, rhythmocardiography, blood pressure, pulse, temperature, psychological testing, clinical and biochemical blood tests, densitometry	Results show an increase in the level an anxiety, stress state and emotional background during the mission. The adaptation process develops gradually, stage by stage, with a minimum efficiency at the beginning, some increase in efficiency in the middle of winter, and its decrease at the end of winter. The polymorphic restructuring of human psychophysiological	Small sample size, males, limited instrument due to the number of participants

for interdisciplinary research in predictive, preventive, and personalized medicine

functions increased tension, and disorder. Regression result indicates a significant effect on blood pressure, atmospheric pressure drops, and background levels of infrasound

Antarctica eye study: a prospective study of the effects of overwintering on ocular parameters and visual function	Stahl MH, Kumar A, Lambert R, Stroud M, Macleod D, Bastawrous A, Peto T, Burton MJ	2018	England	Present the ophthalmological findings of the first Trans-Antarctic Winter Traverse, who overwintered in Antarctica as part of the White Mars Human Science Protocol	Detailed ocular assessment. Team members were asked about any prior ocular problems, eye surgery, including refractive surgery, contact lens or spectacle use and their general health	28–54 years (37 ± 10.3)	Males	Caucasian	5	Pre and post-expedition clinical observations were made including visual acuity, contrast sensitivity, colour vision, auto-refraction, subjective refraction, retinal examination, retinal autofluoresence and retinal thickness, which were graded for comparison. During the expedition additional observations were made on a monthly basis including LogMAR visual acuity, autorefraction and intraocular pressure	LogMAR backlit chart (uncorrected, best corrected (with glasses if available) and pinhole visual acuity), Ishihara chart (contrast sensitivity), LogMAR visual acuity (Peek Acuity, IOP measured and autorefraction), Humphrey 24– 2, autorefraction, subjective refraction, anterior segment, Intraocular pressure (IOP), retinal autofluorecsence, retinal photographs of the disc, macular and vascular arcades	Results showed no significant differences between pre and post-mission observations (i.e., visual acuity, contrast sensitivity, colour vision, refraction, visual fields, intraocular pressure and retinal examination). Retinal thickness decrease across all regions of the retina, except for the macular and fovea	N/A

Assessing Sensorimotor Function Following ISS with Computerized Dynamic Posturography	Wood SJ, Paloski WH, Clark JB	2015	USA	Quantify the initial postflight decrements and recovery of postural stability	Astronaut selection	N/A	N/A	31 Americans, 3 Europeans, 2 Japans & 1 Canadian	37	N/A	Sensory organization tests, motor control tests	Results reported postural instability during unstable-support conditions requiring active head movements.	N/A
Brain Changes in Response to Long Antarctic Expeditions	Stahn AC, Gunga HC, Kohlberg E, Gallinat J, Dinges DF, Kühn S	2019	Germany	Evaluate the effects of physical and social deprivation on the hippocampus	N/A	N/A	5 men, 4 females	N/A	9	Data were collected for brain-derived neurotrophic factor (BDNF) and high-resolution T1- and T2-weighted magnetic resonance imaging (MRI). Imaging and other data were obtained before and after the mission to study changes in the volume of subsections of the hippocampus and of whole-brain gray matter during, before and after polar expedition	MRI, blood sample (BDNF), Spatial processing, Stroop Incongruent Task, Stroop Congruent Task, Digit symbol substitution test	Reduction in the hippocampal volume of the dentate gyrus, in gray-matter volume in the left parahippocampal gyrus, right dorsolateral prefrontal cortex, and left orbitofrontal cortex. BDNF concentration decreased and not reach 1.5 months after the	Small sample size, involvement of possible bias

												baseline values. These were associated with a decrease in dentate gyrus volume, the latter associated with lower cognitive performance	
Cardiovascular Autonomic Adaptation to Long-Term Confinement During a 105-Day Simulated Mars Mission	Wan L, Ogrinz B, Vigo D, Bersenev E, Tuerlinckx F, Van den Bergh O, Aubert AE	2011	Belgium	Examined the effect of physical and mental stresses associated with long-term confinement without the influence of microgravity on cardiovascular responses	Europeans were selected by the ESA. Russians were part of the astronaut team	25 – 40 years (33 ± 6.6)	Males	1 German, 1 French & 4 Russians	6	Blood pressure and heart rate were recorded during a simulation mission on Mars. The breathing cycle was monitored. The data were recorded in five times: 8 to 10 days before the confinement, three times during the confinement (D35, D70, D100) and 8 to 10 days after the exit of the environment. Data were always collected at the same time in the morning. Physical activity and alcohol intake were controlled to avoid bias in the recording the day before the measurements. Caffeine intake was	Beat-by-beat arterial pressure (deriving mean (MAP), diastolic (DAP), and systolic (SAP) blood pressure, heart rate (HR), and the interbeat interval (HRV)), mental stress task (a serial choice reaction time task), arterial blood pressure (photoplethysmograph),	A « U » shape was observed in systolic arterial pressure, diastolic arterial pressure, and mean arterial pressure during the confinement compared to the pre- and post-period. Mental task performance significantly decrease	Small samples, highly selective and homogenous population, subjective stress levels during mental task performance not recorded, wide range of parallel experiments in the

allowed on the morning of data collection	respiratory cycles	the systolic arterial pressure and the mean arterial pressure at the beginning of the mission (reversed changes at other periods). No differences in arterial pressure and heart rate were highlighted between 12 cycle/min, and 6 cycle/min breathing	Mars100 project

Changes in performance and bio-mathematical model performance predictions during 45 days of sleep restriction in a simulated space mission	Flynn-Evans EE, Kirkley C, Young M, Bathurst N, Gregory K, Vogelpohl V, End A, Hillenius S, Pecena Y, Marquez JJ	2020	USA	Determine how rigorously selected, astronaut-like individuals participating in a simulated spaceflight mission would perform during chronic sleep restriction	Participants were required to be non-smokers, 30–55 years of age, have English language proficiency, and at least a Master of Science in a science, technology, engineering, mathematics (STEM) discipline or the equivalent years of experience. Volunteers were required to meet the NASA long-duration space flight physical standards.	30 – 55 years (38.65 ± 8.19)	7 females	N/A	20	N/A		Psychomotor vigilance task (mean reaction time (RT), response speed, lapses, mean RT of 10% fastest responses, mean RT of 10% slowest responses), Samn Perelli, sleep diary	Results showed a progressive reduction in performance throughout the mission. At the end of the mission, they had worst performance. Chronic sleep loss is associated with performance impairment during spaceflight. Subjective fatigue remained unchanged	Earth-based habitat, PVT as a primary measure, no objective sleep data

Exclusion criteria were a body mass index (BMI) greater than 30, height greater than 74 inches, any history of sleep disorders or regular use of sleep aids, any chronic health conditions, regular medication use or had dietary restrictions that could not be stopped during the mission

Changes in sleep patterns during prolonged stays in Antarctica	Bhattacharyya M, Pal MS, Sharma YK, Majumdar D	2008	India	Explore the changes in sleep patterns of six members of the Indian expedition team during their winter stay at Maitri	N/A	35.7 ± 2.32 years	N/A	Indian	6	Polysomnographic sleep recordings were obtained as baseline data in November 2004 in Delhi (altitude 260 m); data on the same parameters were collected at Maitri, Antarctica (altitude 120 m) from January to December 2005. The sleep pattern in each subject was recorded for three consecutive nights at a time. The total recordings for the six subjects spanned about 18 days in each month. During baseline recordings in Delhi in November 2004, two dummy recordings were obtained for each subject during two consecutive nights to get them accustomed to the instrumentation and to sleeping under laboratory conditions. Actual recordings of baseline sleep profiles were made only in the third, fourth and fifth night (i.e. three consecutive nights). Electroencephalogram (EEG), electromyogram (EMG), electrooculogram	Time in bed (TIB), sleep period time (SPT), wake after sleep onset (WASO), movement time (MT), total sleep time (TST), sleep latency, sleep efficiency, the mean sleep cycle time, EEG, EMG, EOG, ECG, SpO2, HR	Results highlighted sleep alterations through a decrease in total sleep time, an increase in duration of waking period after sleep, and sleep latency, a decrease in slow wave sleep and an increase in first stages of sleep as well as rapid eye movement sleep. Also, they showed a variation in most if the sleep parameters with time	No control group

(EOG), electrocardiogram (ECG), peripheral oxygen saturation (SpO_2) and heart rate (HR) measurements during sleep were also recorded

Circadian Levels of Serum Melatonin and Cortisol in relation to Changes in Mood, Sleep, and Neurocognitive Performance, Spanning a Year of Residence in Antarctica	Premkumar M, Sable T, Dhanwal D, Dewan R	2012	India	Evaluate the seasonal variation in serum cortisol and melatonin diurnal rhythms during the polar summer and winter photoperiods, study mood and depression, and assess the change in objective neurocognitive performance of the base personnel over a period of one year in Antarctica	Medical and psychiatric examination and acclimatization training	39 ± 10.24 years	N/A	Indian	20	Serum cortisol and melatonin levels were measured by radioimmunoassay at 8 am, 3 pm, 8 pm, and 2 am in a single day, once each during the polar summer and winter photoperiods. Conventional psychological tests, Depression, Anxiety, and Stress Scale (DASS-42), Epworth Sleepiness Scale (ESS), and a computerized neurocognitive test battery were used to measure mood, sleep, and cognitive performance	Melatonin, cortisol, Epworth Sleepiness Scale (ESS), Morningness Eveningness Questionnaire (MEQ), visual and verbal memory, attention, visual motor speed, arithmetic and reaction times, a modification of the Halstead Reitan Battery, Card Sort Test (CST), Digit Span Forward, Continuous Performance Test (CPT), Stroop Test, Finger Tapping Test, Visual Memory Test, Simple Reaction Time, Choice Reaction	Results revealed the presence of the winter-over syndrome. The diurnal rhythm for cortisol was comparable during the polar summer and winter. Circadian secretion of melatonin was affected during the winter and higher levels persisted throughout the day. Higher 8 am melatonin levels were associated with better sleep quality, lower depression scores, and	N/A

Time, depression, anxiety, and stress scale (DASS-42), Mini Mental Status Examination (MMSE)	better performance (i.e., attention, visual memory, and arithmetic)

Circadian Rhythm and Sleep During Prolonged Antarctic Residence at Chinese Zhongshan Station	Chen N, Wu Q, Xiong Y, Chen G, Song D, Xu C	2016	China	Investigate the changes in circadian rhythm and sleep of expeditioners wintering at Chinese Zhongshan Station	N/A		23–54 years (36.2 ± 9.5)	Males	Chinese	17	Urine samples were obtained every 3–4 hours (longer when asleep) for 48 hours from 17 subjects at 4 time points. Participants were instructed to wear the actigraph on their nondominant wrist for at least 14 consecutive days at 4 periods: November 2010 (departure from Shanghai), March 2011 (before winter), July(mid-winter), and October (end of winter), removing it only for showering. They were asked to press the event marker button on the actigraph each night when they began trying to fall asleep (bedtime) and again when they got out of bed each morning (wakeup time). They were also asked to keep a sleep log of bedtime, wakeup time, and naps for the duration of actigraphic monitoring. The subjects completed the Chinese version of the Horneand Ostberg Morningness-Eveningness Questionnaire and the Chinese version of	Sequential urine samples, aMT6s and creatinine, Octagonal Basic Motionlogger Actigraph, Morningness-Eveningness Questionnaire, Seasonal Pattern Assessment Questionnaire	Results showed sleep problems (i.e., delayed circadian rhythm desynchronization, delayed sleep phase, later chronotype). They highlighted the incidence of subsyndromal seasonal affective disorder (i.e., depression, sleep disorder, increased appetite, weight gain, fatigue, and decreased sociability)	Small samples, only four times points so no consecutive data at monthly intervals, diverse methodology across the papers, actigraph is not best instrument available to record sleep

										Seasonal Pattern Assessment Questionnaire before the departure and in Antarctica (mid-winter).			
Circadian Rhythm of Autonomic Cardiovascular Control During Mars500 Simulated Mission t	Vigo DE, Tuerlinckx F, Ogrinz B, Wan L, Simonelli G, Bersenev E, Van Den Bergh O, Aubert AE	2013	Argentina	Investigate the circadian profile of heart rate variability in the context of the Mars500 study	Astronaut selection	34 ± 5 years	Males	3 Russians, 1 Chinese & 2 Europeans	6	24-hour Holter signals was obtained at 10 time points: in 1 day in the period within the 2 months before confinement (Pre); each 2 months during the confinement period (T1-T8); and in 1 day during the 2nd week after confinement (Post). T1-T4 measurements correspond to the outbound journey, while T5-T8 measurements correspond to the inbound journey. Electrocardiogram signal was recorded	ECG, RRm, SDNN, RMSSD, ln HF, HFnu, ln LF, LFnu, VLF, LF/HF, TP), tdown, tup, HR, circadian rhythms	Results highlighted a decrease in amplitude of the rest-activity pattern of autonomic nervous system parasympathetic function. Confinement induce an increase in mean RR interval, and amplitude of very low and high frequencies. During sleep, high	Small sample size, no control group, only males, highly selected male population, simulation study

													frequency decreased. HRV variables showed nonsignificant circadian rhythms	
Cognitive demand of human sensorimotor performance during an extended space mission: a dual-task study	Bock O, Weigelt C, Bloomberg JJ	2010	Germany	Examine if sensorimotor deficits during spaceflight are related to cognitive overload	Astronaut selection	42–49 years	2 males, 1 female	N/A	3	N/A		Tracking task, reaction time task	Results show deficits in visuomotor performance during spaceflight. Values returned to preflight levels within days.	N/A

Cognitive Performance During Confinement and Sleep Restriction in NASA's Human Exploration Research Analog (HERA)	Nasrini J, Hermosillo E, Dinges DF, Moore TM, Gur RC, Basner M	2020	USA	Investigate the combined effects of confinement, isolation, and sleep deprivation on cognitive performance during spaceflight	Screening for the federally regulated Third-Class Airman Medical Certificate (2019), as well as psychological screening	27 – 53 years (36.0 ± 7.6)	15 males, 17 females	American	32	Cognition was administered to astronaut-like subjects in four 1-week missions (campaign 1) and four 2 weeks missions (campaign 2), with four crewmembers per mission during HERA ground-based facility at Johnson Space Center. Data were collected 3 times pre-mission (Campaign 1: MD-10, MD-3, MD-1 ; Campaign 2: MD-8/9, MD-4, MD-1), on a daily basis during missions (Campaign 1: MD1 – MD7 ; Campaign 2: MD1 – MD14), once additionally in each mission of campaign 2 during the sleep deprivation night, and 3 times post mission (Campaign1:MD+1,MD+6/7,MD+14 ; Campaign2:MD+1,MD+5,MD+7). Bed time was typically scheduled from 11 p.m. until 7 a.m., with one night of sleep restriction or deprivation in each campaign: In campaign 1, subjects were only allowed to go to bed around 3 am on	Cognition test battery (Motor praxis, Visual object learning task, Fractal 2-back, Abstract matching, Line orientation task, Emotion recognition task, Matrix reasoning task, Digit symbol substitution test, Balloon analog risk task, Psychomotor vigilance test)	Results highlighted no negative impact on cognitive performance due to a learning effect (i.e., increased performance). Also, they showed significant improvement in several affective domains across time. Sleep deprivation decreased psychomotor vigilance and cognitive throughput performance	Reported decrease in sleep quality

the night of Mission Day 3 (MD3), with some variations across missions. In campaign 2, subjects were sleep deprived for one full night (from MD10 to MD11), then given a slightly increased sleep opportunity of 10 h on MD11 after being awake for ≈40 h. A survey was administered in each HERA campaign immediately prior to each administration of the Cognition battery including a short altertness survey for campaign 1 and REDCap survey tool (alertness & affect survey) for campaign 2. Both surveys asked subjects to report their time in bed on the previous night; their caffeine, alcohol, or medication consumption; and asked them to rate their tiredness. In addition, the expanded survey in campaign 2 asked subjects to rate their perceived sleep quality, workload, sleepiness, happiness, sickness, physical exhaustion,

										mental fatigue, stress, depression, boredom, loneliness, monotony, and whether they had any conflicts with fellow crewmembers in the past week and how many of those were resolved			
Cognitive performance during long-term residence in a polar environment	John Paul FU, Mandal MK, Ramachandran K, Panwar MR	2010	India	Determine whether there was significant change in cognitive performance by prolonged duration of residence in polar environment	N/A	39.13 ± 9.35 years	23 males, 1 female	N/A	23	Cognitive measures (tests of task acquisition, delayed recognition, attention and concentration, and digit symbol substitution) were obtained at the beginning (second month), the middle (seventh month) and the final (twelfth month) phases of prolonged residence in Antarctica	Task Acquisition, Delayed Recognition, test of Attention and Concentration in PGI Memory Scale, The Digit Symbol of WAIS-R	Results showed a significant increase in recognition memory and learning. Stable performance over the mission was found for short-term memory	No control group, percent accuracy measured as an indicator of cognitive performance, only three sessions of cognitive performance assessment

Confinement has no effect on visual space perception: The results of the Mars-500 experiment	Sikl R, Simeček M	2013	Czech Republic	Investigate whether and to what extent the crewmembers were able to ignore 3-D contextual information when estimating the relative 2-D lengths of the lines that stood in front of the background scene ; whether crewmembers could extract and apply perspective information from the 3-D environment when matching the size of objects that are a natural part of the visual scene ; the perceptual salience of farther versus closer	N/A	27 – 38 years (mean age 32.0 years)	Males	3 Russians, 1 French, 1 Italian & 1 Chinese	6	The subjects took part in a total of 10 experimental sessions. The baseline session was conducted two weeks before the mission began, eight sessions took place during confinement, and the last session took place seven days after confinement ended. The schedule of the « in-flight » sessions was as follows: Week 2, Month 2, Month 3, Month 5, Month 8, Month 10, Month 13, and Month 15. The control group had an identical schedule. Each session required approximately 45 min to complete the presented set of tasks. The experimental battery consisted of nine experiments examining the crewmembers' visual space perception, but also their face and object recognition. In any particular session, the crewmembers conducted only some of the experiments in the battery, typically five or six. Consequently, unequal numbers of measurements were	N/A	Results of the 2D perception revealed alterations in perception. However, the 3D perception of the crew members may not have changed significantly across the mission	Experiments computer administered, tests administered as part of a larger battery of tests each day, heterogeneous group

objects in the visual environment using a change-detection task, (4) test whether the crewmembers' visual space was isotropic in every direction	taken during each experiment, and also individual experiments were performed during various phases of isolation

Coping with Antarctic demands: Psychological implications of isolation and confinement	Tortello C, Folgueira A, Nicolas M, Cuiuli JM, Cairoli G, Crippa V, Barbarito M, Abulafia C, Golombek DA, Vigo DE, Plano SA	2020	International	Assess mood variations and coping strategies, as well as their possible modulation by group dynamics in a crew at the Belgrano II Argentine Antarctic Station throughout 1 year of confinement.	N/A	34 ± 1 year	N/A	N/A	13	Participants completed emotional, coping and social dynamics questionnaires bimonthly in March, May, July, September and November	Beck Depression Inventory-II (BDI-II), Beck Anxiety Inventory (BAI), short version of the COPE scale, defence Style Questionnaire (DSQ40), Recovery and Stress questionnaire (RESTQ)	Results highlight a significant decline in social dynamics scales (i.e., decreases in perceived peer, hierarchical support). Coping strategies showed a decrease in mature defence throughout the expedition. A positive correlation was found between social support and recovery from stress	Small sample size, the lack of an objective measures to complement the subjective assessment, absence of a control group in the mainland, no positive affect assessment

Cortical reorganization in an astronaut's brain after long-duration spaceflight	Demertzi A, Van Ombergen A, Tomilovskaya E et al	2016	Europe	Caracterize the impact of long-duration spaceflight on brain function in a single cosmonaut, measured by functional MRI.	Astronaut selection	44 years	Males	Russian	7 (6 controls, one cosmonaut)	N/A			Functional magnetic resonance imaging	Brain function induced by long-duration spaceflight were altered in vestibular and motor-related regions (e.g., lower resting state connectivity for the right insula and between the left cerebellum and the right motor cortex). Alos, less connexion were reported during resting-state in the motor cortex. The precentral as well as postcentral gyrus and cerebellum	N/A

												are linked with voluntary motor initiation, proprioception, and motor coordination. Also, results show a decreased resting state connectivity in the right insula postflight.	
Different adaptations of Chinese winter-over expeditioners during prolonged Antarctic and sub-Antarctic residence	Chen N, Wu Q, Li H, Zhang T, Xu C	2016	China	Understand the different patterns of psychophysiological responses provoked by environmental stress	Medical and psychological examination (no psychiatric disorder, any medication that potentially affected the study)	N/A	N/A	Chinese	28 (12 Great Wall Station, 16 Zhongshan Station)	Subjects are winterers in two groups of Chinese expeditioners who were deployed to sub-Antarctic (Great Wall Station) and Antarctic (Zhongshan Station) from December 2003 to 2005. Measures of mood was obtained at departure from China, mid-winter (Antarctica), end of winter (Antarctica), and return to China, respectively. All participants were weighed, measured, and registered for blood pressure at departure and return, respectively	Blood pressure HR, Chinese version of Profile of Mood States (POMS)	Crewmembers showed different change patterns in mood. Negative mood was positively associated with the severity of environment. No significant differences between the two winterers' groups	Small numbers of eligible study participants and an inability to obtain the consecutive data at monthly intervals, diversity of the instruments and analysis methods employed

												were found for systolic and diastolic blood pressure	in the physiological and psychological assessments
During the Long Way to Mars: Effects of 520 Days of Confinement (Mars500) on the Assessment of Affective Stimuli and Stage Alteration in Mood and Plasma Hormone Levels	Wang Y, Jing X, Lv K, Wu B, Bai Y, Luo Y, Chen S, Li Y	2014	China	Investigate emotional responses and psychological adaptation over longterm confinement	Consideration of psycho-physiological health, language, occupation background and so on	32.46 ± 8 years	Males	3 Russians, 2 Europeans & 1 Chinese	6	During the confinement, the crew followed the working schedule to carry out 8 timed tests, which was sent into the module via specific local network ahead of one week. Subjects were asked to undertake POMS prior to IAPS. At the beginning of each test, the instructions were provided in three languages. The specific days of blood sampling were close to the days of POMS and IAPS data acquisition. After collection and pretreatment, the blood samples were sent out immediately via a special air-lock. On +7 d after isolation, a detailed interview recording with both hand and video was	International Affective Pictures System (IAPS),Profile of Mood States (POMS), cortisol, 5-hydroxy tryptamine, dopamine, and norepinephrine, interviews	Crewmembers tended to assign positive ratings to negative pictures with time. Correlation between psychological and biochemical data was found	Non-controlled design and the small sample size, non-coincidence between testing days of IAPS & POMS and blood sampling days

										made for each crewmember			
Dynamics of stress and recovery and relationships with perceived environmental mastery in extreme environments	Nicolas M, Martinent G, Suedfeld P	2022	International	Examien dynamics of stress/recovery responses during one-year at two polar stations characterized by specific environmental conditions and the effects of perceived environmental mastery on both stress and recovery responses	Medical and psychological screening based on psychological questionnaires and interviews	20 – 51 years (35.80 ± 14.56) (Kerguelen station), 19 – 47 years (33.45 ± 13.27) (Dumont d'Urville)	15 men, 3 women (Kerguelen station), 21 men, 4 women (Dumont d'Urville)	N/A	53 (28 Kerguelen, 25 Dumont d'Urville)	Subjects completed both the RESTQ-48 questionnaire and environment mastery scale the first day on the station, and only the RESTQ-48 at five months, eight months and one year	RESTQ-49, environment mastery scale	Results reported a linear decrease in fatigue, conflicts, pressure, and general well-being in Dumont d'Urville. During winter, social stress linearly increased both at Kerguelen and Dumont d'Urville, success only at Dumont d'Urville. Low level of	Small sample size, limited measures, interindividual variability

environmenral mastery was negatively associated with lack of energy, somatic complaints at both stations, and stress, conflicts/pressure at Dumont d'Urville. High level of environmental mastery was positively associated with somatic relaxation, general well-being at both stations and success, sleep quality, recovery at Dumont d'Urville.

Environme
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Effects of Long-Term Isolation and Anticipation of Significant Event on Sleep: Results of the Project « Mars 520 »	Zavalko IM, Rasskazova EI, Gordeev SA, Palatov SU,Kovrov GV	2013	Russia	Study the effects of long-term isolation on night sleep of the healthy human	Medical control and preselection	27 – 38 years	Males	3 Russians, 2 Europeans & 1 Chinese	6	The sleep recording (polysomnography) started when the astronaut decided to go to bed and stopped at the spontaneous awakening the next morning. Recordings were made in six times, each consisting of two consecutive nights. The baseline was performed 10 weeks before entry into the capsule, four measurements took place during the mission (six weeks after the simulated lift-off, two weeks before the simulated arrival on Mars, two weeks after the simulated departure from Mars and ten weeks before the return to Earth) and a last measurement was recorded two weeks after the exit from the environment.	(1) time in bed (TIB)—period (in min) from light off to the end of the recording; (2) sleep latency—period from light off to the sleep onset; (3) delta sleep latency—period from sleep onset to the first epoch of delta sleep; (4) REM latency—period from sleep onset to the first epoch of REM sleep; (5) total sleep time (TST)—the sum of stage 1, stage 2, delta and REM sleep duration in min; (6) sleep efficiency (in %)—ratio of TST in TIB; (7) percent of stage 1, stage 2, delta and	Results highlight a prolongation of sleep latency and a reduction in sleep efficiency. At important time of the mission, the frequency of the nights with low sleep efficiency increased. Anticipation would be a factor in sleep modification, notably at the end of confinement	Small samples, personal differences in sleep response on stress, important mild stressors, high selective compatible, psychological, healthy and adaptable crew, only focus on night sleep, several recordings lots due to technical problems

REM sleep—ratio (in %) of duration of the stage to TST; (8) wake after sleep onset (WASO)—duration of wake during a period from sleep onset to the end of the recording; (9) arousal index—total amount of arousal per TST and multiply by 60.

Environmental influences on hypothalamic-pituitary-thyroid function and behavior in Antarctica	Palinkas LA, Reedy KR, Shepanek M, Smith M, Anghel M, Steel GD, Reeves D, Case HS, Do NV, Reed HL	2007	USA	Examine the physiological and psychological status of winterers in Antarctica at McMurdo and South Pole stations to determine whether there were any significant differences by severity of the stations' physical environment	N/A	N/A	122 males, 63 females	N/A	185	N/A		Blood pressure, heart rate, T3, cortisol, Continuous performance task, Logical reasoning syntax, Matching-to-sample, Simple reaction timeSternberg Memory Search, Adjective checklist mood including vigor, happiness, fatigue, depression, anger, anxiety	Results identified the Polar T3 Syndrome and an increased physiological responses to colder temperatures and/or higher altitude at South Pole.	Small sample size, important time period between pre and post-intervention measures, multiple comparisons, missing informations on the extent of outdoor exposure

Exposure to an extreme environment comes at a sensorimotor cost	Kim KJ, Gimmon Y, Sorathia S, Beaton KH, Schubert MC	2018	USA	Develop a Portable Sensorimotor Assessment Platform (PSAP) to enable a crewmember to independently and quickly assess his/her sensorimotor function during the NASA's Extreme Environment Mission Operations (NEEMO) and investigate changes in performance of static posture, tandem gait, and lower limb ataxia due to exposure in an extreme environment	N/A	N/A	N/A	N/A	15 (10 crew members, 5 control subjects)	Subjects assessed their sensorimotor function using the Portable Sensorimotor Assessment Platform (PSAP). PSAP is based on five body-worn inertial sensors, MTw Xsens sensor units, that record kinematic data. Each unit comprises an accelerometer, gyroscope, and magnetometer. Five sensors were placed including the head, trunk, pelvis, left and right ankles. Sessions consisted of three tests: (1) Tandem Walk test, (2) Prone-to-Stand, and (3) « S » « N » « O » « W » letter leg-writing test. Each test was done with eyes open (EO) and again with eyes closed (EC). Each of the ten crewmembers participated in both a pre-mission training session and baseline data collection at the JSC. During the mission weeks in Florida, data was collected on mission day 2, mid-mission, and finally post-mission within a	The variables for the tandem walk test were: Displacement Area of Head, Trunk and Pelvis, and right and left Gait Regularity Mean, SD, and Range. The variables for Prone-to-Stand test were: total sway area and maximum ML and AP sway excursion. The variables for SNOW test were: jerk during horizontal and vertical movements, and sample entropy of horizontal and vertical motions	Changes in sensorimotor performance lead to body movement abnormalities (i.e., upper body balance, tandem walking) throughout the mission	Small sample size, some of the variables developed to measure gait did reveal behavioral change during tandem walk, non-gait tasks are not as sensitive to identify sensorimotor change in the NEEMO environment

few hours of returning
to land

Extreme Environment Effects on Cognitive Functions: A Longitudinal Study in High Altitude in Antarctica	Barkaszi I, Takács E, Czigler I, Balázs L	2016	Hungary	Investigate the impact of long-term Antarctic conditions on cognitive processes	N/A	20 – 55 years	Males	6 French, 6 Italians & 1 British	13	Behavioral responses and event-related potentials were recorded during an auditory distraction task and an attention network paradigm. Beyond the hypoxia, the fluctuation of sunshine duration, isolation and confinement were the main stress factors of this environment. Data were recorded once approximately every 6 weeks. Each subject participated in a 4-day-long fixed-sequence measurement	EEG, auditory distraction paradigm which include prolonged reaction time and higher error rate accompanied by a series of ERP components (N1/MMN, P3a and reorienting negativity), Attention Network Test (ANT), N2 component, P3 complex (orientation-related P3a, the target-related P3b, and the no-go P3), event-related potential components	Results showed no negative impacts on cognitive activity during the winter	Lack of baseline data collection before the expedition and the lack of control group

Hormonal, autonomic cardiac and mood states changes during an Antarctic expedition: From ship travel to camping in Snow Island	Moraes MM, Bruzzi RS, Martins YAT, Mendes TT, Maluf CB, Ladeira RVP, Núñez-Espinosa C, Soares DD, Wanner SP, Arantes RME	2020	Brazil	Evaluate the influence of an Antarctic expedition, consisting of 26-day travel on board a ship followed by 24-day camping in the Antarctic field, on hormonal responses, autonomic cardiac control, and mood states in individuals that were born and live in tropical regions	N/A	N/A	7 men and 3 females	N/A	10	Data collection was carried out on the 2nd, 16th, and 26th days aboard the ship (characterized by exposure to low-luminosity and temperature-controlled environments) and on the 4th, 11th, and 23rd days of camping in the Antarctic field (prolonged exposure to natural luminosity and cold environments).Resting heart rate variability (HRV) was recorded, and the volunteers answered a mood questionnaire. Samples of saliva for measurement of melatonin concentration were obtained at night	Cortisol concentration, HRV (NN, NN50, pNN50, HF, LF, LF/HF ratio), melatonin concentration, Brunel Mood Scale (BRUMS)	Ship travel and camping in Antarctica induced specific changes in cardiac autonomic regulation, as well as in mood states (e.g., increases in depression score), reduced cortisol, biphasic changes in HRV parameters for travel vs. increased cortisol and oscillations in tension and confusion for camping)	Results limited to the conditions of Antarctic research expeditions and camping, heterogeneous sample

How stressful are 105 days of isolation? Sleep EEG patterns and tonic cortisol in healthy volunteers simulating manned flight to Mars	Gemignani A, Piarulli A, Menicucci D, Laurino M, Rota G, Mastorci F, Gushin V, Shevchenko O, Garbella E, Pingitore A, Sebastiani L, Bergamasco M, L'Abbate A, Allegrini P, Bedini R	2014	Italy	Evaluate the relationships between stress related to social/environmental confinement and sleep in six healthy volunteers involved in the simulation of human flight to Mars (MARS500)	Astronaut selection	33 ± 6 years	Males	N/A	6	Sleep EEG, urinary cortisol (24h preceding sleep EEG recording) and subjectively perceived stress levels were collected. Cognitive abilities and emotional state were evaluated before and after the simulation. Sleep EEG parameters in the time (latency, duration) and frequency (power and hemispheric lateralization) domains were evaluated. The design included 5 time points: BDC, T1, T2, T3, RDC. Sleep and stress levels were evaluated at each time-point, while the neuropsychological evaluation was performed only during BDC and RDC	EEG, urinary cortisol, Wechsler Memory Scale, Corsi block test, Kohs Cubes test, Profile of Mood States (POMS), Perceived Stress Scale (PSS)	Stressful conditions alter sleep structure and sleep EEG spectral content leading to pathologies (i.e., insomnia). Correlations between cortisol fluctuations and sleep changes were found. No effect of prolonged confinement was found either for cognitive abilities or emotional state	Small sample size, no generalization

Human change and adaptation in Antarctica: Psychological research on Antarctic wintering-over at Syowa station	Kuwabara T, Naruiwa N, Kawabe T, Kato N, Sasaki A, Ikeda A, Otani S, Imura S, Watanabe K, Ohno G	2021	Japan	Focus on the individuality of each drawing, believing that qualitatively comprehending messages from them would be a clue to understanding the hearts and minds of the wintering team members	Undergo medical screening, including psychological tests, volunteer	20 – 60 years	161 males, 11 females	Japanese	30	This research conducted a survey of five wintering-over teams and measured each of them six times	Baum test, the Positive and Negative Affect Schedule (PANAS), the Coping Orientation to Problems Experienced (COPE), Subjective Health Complaints Inventory (SHC), and medical consultations	Results revealed fewer physical health risks in Antarctica than in Japan. Crew members from Antarctica reinterpreted situations positively and accepted their environment (i.e., instrumental social support, planned ahead, active coping skills, humour). They did not act out emotionally or deny problems and positive affect remained	N/A

												constant during the wintering. Stability or flexible adjustment to a new life coping were highlighted as strategies to overcome this period	
Human factors research as part of a Mars exploration analogue mission on Devon Island	Binsted K, Kobrick RL, Griofa MÓ, Bishop S, Lapierre J	2010	USA	Provide an overview of six human factors studies that took place during F-XI LDM, and make a case for an ongoing program of HF research conducted during analogue missions	N/A	24 – 38 years	4 males, 3 females	N/A	7	Before the four-month Arctic expedition, there was a two-week crew training rotation. FHFS-03: evaluate design space using PHADES, evaluate monthly cognitive performance utilizing a software cognitive assessment tool (WinSCAT: Spaceflight Cognitive Assessment Tool for Windows); and to investigate the interaction of personality, stress and coping styles upon group dynamics using a composite battery of assessments through an online survey site (SurveyMonkey.com). FHFS-04 and FHFS-06:	PHADES, Winscat, CASPER, DST, RTT, composite battery of assessment evaluating stress and coping styles	Results suggest psychological impact (e.g., sleep disorders, stress). Although cognitive modifications occurred, no signs cognitive ability decrements was highlighted. Women were engaged in more active coping	N/A

										CASPER (Cardiac Adapted Sleep Parameter Electrocardiogram Recorder) was used to monitor sleep. As part of this mission each crewmember completed both subjective and objective testing including a computer-based decision speed test (DST) and reaction time test (RTT). Both of these measurements were completed twice daily (pre- and post-sleep) before, during and after the Martian sol period of 37 days. The reaction test involved timed reaction to visual stimuli, while the decision test involved timed identification and recognition		strategies than man	
Investigating human cognitive performance during spaceflight	Pattyn N, Migeotte PF, Demaeseleer W, Kolinsky R, Morais J, Zizi M	2005	Belgium	Explore the possibility to maximize both the validity and the sensitivity of discrepancy between subjective evaluation and	N/A	N/A	N/A	American	14 (13 controls, one astronaut)	N/A	Colour-word Stroop task, general emotional Stroop task, specific emotional Stroop task, recognition task,numerical Stroop task, hyperventilation	Cognitive functions were impacted during space flight.	N/A

				experimental results									
Locus of Control, Stress Resistance, and Personal Growth of Participants in the Mars-500 Experiment	Solcova I, Vinokhodova AG	2015	Russia	Assess stress resistance and ability to control own emotions voluntarily	N/A	27 – 38 years (32.16 ± 4.99)	Males	N/A	6	At the baseline measurement, the following questionnaires were administered to the participants: Locus of Control, Brief Resilient Coping Scale, and Proactive Coping Scale. The follow-up measurement took place in November 2011. After the experiment (three weeks after the isolation finished), testing was made in order to assess changes in a locus of control, resilient coping, and proactive coping. The « stress-related growth » scale was used in the second follow-up measurement after the isolation finished. To make the Relaxometer test, the actual value of electric skin resistance (ESR) (in kiloohms) was monitored. When	Locus of Control (Visual Analog Scale), Stress-Related Growth Scale (SRGS), Proactive Coping Inventory (PCI), « Relaxometer » computerized technique, electric skin resistance (ESR; level of ESR, average level of ESR, relative changes of ESR in %), Mirror Coordinograph computerized test, HR,	Results highlighted the ability of the crew to engage in resilient coping and emotional stability	N/A

										solving a complex task which causes a perceptive-motor conflict, a number of psychophysiological parameters (heart rate and its variability, level of ESR before and after testing) were registered, which enable the assessment of emotional reactions, self-control, and « physiological cost » of activity	HRV, Luscher eight-color test		
Long-duration spaceflight adversely affects post-landing operator proficiency.	Moore ST, Dilda V, Morris TR, Yungher DA, MacDougall HG, Wood SJ	2019	USA & Australia	Assess the impact of long-duration spaceflight on operator proficiency and cognitive/sensorimotor tests to determine the underlying cause of any post-flight performance decrements	Astronaut selection	47.5 ± 6.7 years for astronauts ; 39.0 ± 9.7 for shadow; 40.0 ± 10.6 for sleep deprivation group	Males for astronauts; 20 males for shadow; 5 males and 4 females for sleep deprivation	N/A	29 (8 astronauts, 12 shadow, 9 sleep deprivation)	A cognitive and sensorimotor test battery for astronauts was collected four times preflight and three times postflight. This schedule was the same for the shadow group. For the fleep deprivation group, subjects performed three baseline sessions and a post session after 30 hours of sleep deprivation. Sleep and psychomotor vigilance were recorded for this group	Stanford sleepiness Scale, Static Visual Acuity, Manual Dexterity, Simple Reaction Time, Perspective Taking, Match to Sample, Manual Tracking, Dual Tasking, Motion Perceptionmo	Results identified an increase in sleepness on landing day for astronauts, similar to the sleep deprivation group. They report deficits in manual dexterity, in dual-tasking and motion	N/A

											tion simulator, Choice of Simulation Task, Psychomotor Vigilance test, driving simulations	perception, and in a striking degradation in the ability to operate a vehicle, specially in post landing. These ones were not only attributed to fatigue. Astronauts recovered after 4 days postflight.	
Mars 520-d mission simulation reveals protracted crew hypokinesis and alterations of sleep duration and timing	Basner M, Dinges DF, Mollicone D, Ecker A, Jones CW, Hyder EC, Di Antonio A, Savelev I, Kan K, Goel N, Morukov BV, Sutton JP	2013	USA	Record objective neurobehavioral data on the activity patterns of a multinational, culturally culturally diverse crew	N/A	N/A	N/A	International crew	6	Wrist actigraphy (Actiwatch Spectrum; Philips/Respironics) for assessing sleep–wake activity was worn by crewmembers throughout the 520 d. Both average light intensity and movement-induced accelerations at the wrist were recorded in 1-min epochs. Spectrographic analyses of actigraphy data were performed on 1-min epochs to determine the predominant periodicity of sleep–wake timing for each subject.	Sleep–wake activity, predominant periodicity of sleep–wake timing, psychomotor vigilance performance(PVT-B), computerized scales that included 100-mm visual analog scales	Results showed sleep troubles, a link between performance deficits and sleep deprivation and subjective sleep quality	N/A

										Behavioral alertness was assessed by using psychomotor vigilance performance on a 3-min test (PVT-B) that was obtained weekly (once in the morning, once in the evening). Immediately before or after each PVT-B test, crewmembers completed computerized scales that included 100-mm visual analog scales with the following binary anchors: good/poor sleep quality (morning only), high/low workload (evening only), and high/ low tiredness (evening only)			
Mars-105 study: Time-courses and relationships between coping, defense mechanisms, emotions and depression	Nicolas M, Sandal G, Weiss K, Yusupova A	2013	Europe	Investigate the time-courses and the relationships between coping, defense mechanisms, emotions and depression considered as key factors in adaptation to ICE	Clinical examination, both medical and psychological	25 – 40 years (32.7 ± 5.9)	Males	4 Russians, 1 German & 1 French	6	Psychological measures were assessed at baseline 14, 7, 3 days before ICE period (BDC 1, BDC 2, BDC 3), at 1, 23, 44, 65, 86 and 99 days for the ICE period (ICE 1, ICE 2, ICE 3, ICE 4, ICE 5 and ICE 6), and in post-ICE period at þ1, þ3 and þ7 days after the ICE period (Post 1, Post 2, Post 3).	COPE scale, Beck Depression Inventory-II (BDI-II), Positive Affect Negative Affect Schedule (PANAS), Defense Style Questionnaire assesses an individual's conscious derivatives of	Results showed a significant decrease in positive emotion, and the relations of defense to both coping and emotions, and thus psychological states	Small sample size, limits from the environment, rigorous selection of the participants, difficulties to reach significant analyses,

				environments							defense mechanisms (DSQ)		use of self-reports
Mental and Physical Workload, Salivary Stress Biomarkers and Taste Perception: Mars Desert Research Station Expedition	Rai B, Kaur J	2016	USA & India	Find the effects of physical and mental workload on taste sensitivity and salivary stress biomarkers	N/A	25 – 40 years (32.7 ± 5.9)	N/A	N/A	12	Taste reactions and intensity of the taste sensations to quinine sulfate, citric acid, and sucrose were tested before and after mental and physical tasks for one hour. Also, psychological mood states by profile of mood state, salivary, salivary alpha amylase and cortisol, and current stress test scores were measured before and after mental and physical tasks. The subjects were divided into one group starting at 10:30 and second group starting at 13:30. Every subject was tested for one session (for example, control condition and mental	Profile of mood state (POMS), Time Intensity (TI) test, Current stress test (CST), cortisol, letter search task	Results showed a reduction of the duration of taste. These effects were more pronounced in physical as compared to mental tasks	N/A

workload condition) for 1 day. Each session lasted for about 1 h. Each crew member participated in both the mental and physical workload 30 sessions for each. Physical workload tasks were measuring extravehicular activities for soil and rock sampling. The taste stimuli were exemplars of the sensations of bitterness, sourness, and sweetness. The bitter sample was an aqueous solution of quinine sulfate (1.82 ± 10-5 M). The sour sample was an aqueous solution of anhydrous citric acid (1.37 ± 10-2 M), and the sweet sample was an aqueous solution of sucrose (2.63 ± 10-1 M). For the physical workload, individuals did extravehicular activity for 1 h. The purpose of the mental workload was to produce mental fatigue; the performance of subjects was unimportant

Modulations of Neuroendocrine Stress Responses During Confinement in Antarctica and the Role of Hypobaric Hypoxia	Strewe C, Thieme D, Dangoisse C, Fiedel B, van den Berg F, Bauer H, Salam AP, Gössmann-Lang P, Campolongo P, Moser D, Quintens R, Moreels M, Baatout S, Kohlberg E, Schelling G, Choukèr A, Feuerecker M	2018	Europe	Evaluate the psychological stress over a period of 11 months including winter confinement	N/A	N/A	Males	N/A	31 (15 subjects Concordia, 16 Neumayer III)	Data from two expedition campaigns at Concordia (high altitude) (2016 and 2017) and from three expedition campaigns at Neumayer III (sea level) (2013–2015) were analyzed. Data collection in the study groups were performed on a monthly basis and in the morning for cortisol during the first week of the month starting in January/February after arrival of the crew members and continued through the whole year until October/November when the station was prepared for the next seasonal change of crew. Two different paper questionnaires were performed to quantify and analyze each participant's emotional stress level	Short Questionnaire on Current Stress (CST), Spielberger State Trait Anxiety Inventory (STAI), cortisol	A year in Antarctica showed a distinct modulating effect on stress response (i.e., Concordia stations vs. Neumayer III station). Results are not associated with psychological stress	Neumayer III crew is not an ideal control group, physical conditions and fitness might interfere with the measures, a possible influence of the climate on the measures made cannot fully be excluded, highly motivated and well prepared individuals

Multi-System Adaptation to Confinement During the 180-Day Controlled Ecological Life Support System (CELSS) Experiment	Yuan M, Custaud MA, Xu Z, Wang J, Yuan M, Tafforin C, Treffel L, Arbeille P, Nicolas M, Gharib C, Gauquelin-Koch G, Arnaud L, Lloret JC, Li Y, Navasiolava N	2019	China	Study physiological and psychological consequences of a confinement in an Controlled Ecological Life Support System	Volunteers based on qualification review and physical and psychological checks	34.2 ± 6.6 years	3 males, 1 female	Chinese	4		Body composition, heart, large vessels, and muscle tone were studied. Behavioral activities were studied by ethological monitoring; psychological state was assessed by questionnaires. Measurements and samplings were carried out at eight time points: Baseline data collection prior to confinement (B), six time-points for each month of confinement (M1 to M6), and Recovery data collection post-confinement (R). The subjects were trained to perform measurements and samplings by themselves as usually occurs during isolation studies and space missions. Finger blood pressure wave and ECG were recorded continuously for 10 min at rest in a seated position. Measurements for ultrasounds were performed at the cardiac, carotid, and portal levels	Body weight, lean and fat mass, total, cortisol, ECG, blood pressure, ultrasound examinations, skin blood flow assessment, HRV, hand-held myotonometer, muscle tone, visual analog scale, hand-to-ground distance during forward flexion, ethological monitoring (i.e., personal and interpersonal actions, facial expressions, body position), Recovery-Stress Questionnaire (RESTQ), Positive Affect – Negative	Results highlighted that environment not systematically induce additional stress and impaired physiological as well as psychological states. They reported adaptive responses across time, especially during the first months of confinement (i.e., increased emotional adaptation) and inter-individual differences	CELSS not comparable with Mars 500 experiment

Affect Schedule (PANAS), Isolated and Confined Environments Questionnaire (ICE-Q)

Neurophysiological, neuropsychological, and cognitive effects of 30 days of isolation	Weber J, Javelle F, Klein T, Foitschik T, Crucian B, Schneider S, Abeln V	2019	International	Investigate the effects of short-term isolation (30 days) on mood, cognition, cortisol, neurotrophic factors, and brain activity	Astronaut selection (hold a bachelor's degree in a natural-science-related field and must have shown the motivation to and « work ethic similar to the astronaut stereotype », NASA long-duration space flight physical)	36.3 ± 7.2 years for confined and 31.8 ± 8.7 years for control	7 females (confined), 9 females (control)	N/A	33 (16 confined, 17 non-isolated)	Participants were divided between 4 missions (confined IG vs. controlled CG). Control subject needed to perform at least 3 times of physical activity per week which was monitored via pulse monitors and training documentation. Participants of both IG and CG completed 5 measurement sessions. Multiple tests including the Positive and Negative Affect Schedule-X and cognitive tests were conducted, and a 5-min resting electroencephalography was recorded. A fasted morning blood drawing was also done. Baseline measures were recorded 5 days prior to the start of isolation [Mission Day − 5 (MD − 5)]. Within the 30 days of isolation, measurements were carried out on Mission Days 7, 14, and 28 (MD 7, 14, 28). A post-test was carried out 5 days after the end of the isolation period [Mission Day + 5 (MD + 5)]	EEG, Positive and Negative Affect Schedule-X (PANAS-X), Memory matrix, Speed match, Chalkboard challenge, and cortisol	30 days of isolation has no significant effect on cortical activity, cognition, and mood. Cortisol levels were significantly increased during isolation with a neural adaptation	Confined participated would increase their chances to be considered for further astronaut selections, and may influence the results between both groups; lack of high power due to small sample size

Neurovestibular Symptoms in Astronauts Immediately after Space Shuttle and International Space Station Missions	Reschke MF, Good EF, Clément GR	2017	USA	Assess vestibular changes and related sensorimotor difficulties, especially instability of posture and gait, among astronauts immediately after they return from space and to compare the effects experienced after short- and long-duration space missions	Astronaut selection	45.5 ± 6.1 years	16 males , 2 females	N/A	18	N/A		Gaze-evoked nystagmus, motor tests (pointing, chair stand test, postural stability, tandem walking, questionnaires (symptoms, subjective reports)	Spaceflight induced walking and postural instabilities. Astronauts reported an exaggerated perceived motion associated with sudden head movements during reentry and after landing.	N/A

Physiological phenotypes and urinary metabolites associated with the T psychological changes of healthy human: A study in ‘‘lunar palace 365”	Hao Z, Fenga S, Zhua Y, Yanga J, Menga C, Hua D, Liua H, Liua H	2020	China	Study the objective recognition indicators such as physiological phenotypes and urinary metabolites associated with the psychological changes of crewmembers in isolated and confined environments	After being trained for equipment operation and troubleshooting, performances of each candidate were evaluated by doing tasks needed for the BLSS experiment, including cultivating and harvesting plants, breeding yellow mealworms, disposing wastes…	25 – 30 years	4 males and 4 females	Chinese	8	Phenotypic measurements were recorded daily. Psychological measurements were completed 1–2 times per week, while 24-h urine samples were collected for metabolomics analysis on the day of psychological measurement. Semi-structured interviews were also performed weekly during the experiment to provide in-depth qualitative data. Body weight, lean body mass, body mass index were measured and recorded after defecation and urination and before breakfast. Body temperature, oxygen saturation, pulse rate, blood pressure, and heart rate were measured and recorded every morning and evening. Step count and calorie consumption was measured and recorded by the portable activity measuring instrument. he volume of drinking water (only direct drinking water) was recorded every time, then the total volume	Symptom checklist 90 (SCL-90), profile of mood states (POMS), urine, interviews, body weight, lean body mass, body mass index, body temperature, oxygen saturation, pulse rate, blood pressure, and heart rate, sleep conditions (number of falling asleep before 12:00 a.m., number of night awakenings, total sleep time, deep sleep time, light sleep time), urination and stool conditions, activity conditions, water intake	Results suggest that crewmembers had lower negative mood scores and higher positive mood scores when they performed their missions the second time than the first. Cardiovascular changes were associated with psychological states. They show high inter-individual differences	Small sample size, strong individual differences, simulated in Lunar expedition (absence of microgravity, radiation and threat-to-life)

was calculated before going to bed. Menstrual status (menstruation) was also recorded by female crewmembers daily	and menstrual status, step count and calorie consumption

Preparing for Mars: human sleep and performance during a 13 month stay in Antarctica	Mairesse O, MacDonald-Nethercott E, Neu D, Tellez HF, Dessy E, Neyt X, Meeusen R, Pattyn N	2018	International	Contribute to a better understanding of sleep in space by assessing objective sleep parameters, daytime sleepiness and fatigue, and psychomotor performance during a prolonged stay in an Antarctic space analog	Medical and psychological profiling	20 – 55 years (34.54 ± 9.46)	N/A	French & Italians	13	Upon arrival at the station, participants' acclimatization was monitored weekly through physical examination, mood questionnaires, pulsed oxygen saturation (SpO2), and Lake Louise questionnaires. Sleep monitoring started between 2 and 3 months after arrival, long after the symptoms of acute mountain sickness had resolved, and after the time during which acclimatization should occur. During the winter-over, participants performed eight measurement cycles approximately every 6 weeks (two measurements per Antarctic season: cycles 1 and 2: Late Summer (LS) from January to March, cycles 3 and 4: Early Winter (EW) from late March to June, cycles 5 and 6: Late Winter (LW) from late June to late August, and cycles 7 and 8: Early Summer (ES) from September to November). Each of the cycles comprised an	Polysomnography (EEG, EOG, EMG), capillary oxygen saturation, visual reaction time (RT) task, Epworth Sleepiness Scale (ESS), Fatigue Severity Scale (FSS), Karolinska Sleepiness Scale	Results suggest high-altitude periodic breathing, increased sleep onset latencies, and reduced psychomotor speed	Small samples, for limited periods of time and produce therefore hardly generalizable data

										embedded 4 day program of several physiological measurements including all-night PSG. Participants had at least one habituation night to familiarize them with the equipment			
Prolonged Microgravity Affects Human Brain Structure and Function.	Roberts DR, Asemani D, Nietert PJ, Eckert MA, Inglesby DC, Bloomberg JJ, George MS, Brown TR	2019	USA	Investigate whether these structural changes are associated with alterations in motor or cognitive function	Astronaut selection	46.7± 2.1 years for short spaceflight; 47.5 ± 4.8 years for long missions	16 males, 3 females	N/A	19	Brain magnetic raisonnance imagery was performed before and within 3 weeks following spaceflight. Participants completed the WinSCAT cognitive battery 6 times before the mission, every 30 days on board the ISS and one month following the return. The FTT motor task recorded 100 and 60 days before the mission and within 24-48 days following the end	Functional magnetic resonance imaging, WinSCAT, Functional Task Test (FTT)	Brain structural changes are associated with changes in cognitive and motor test scores and with the development of spaceflight-associated neuro-occular syndrome.	Small sample size, under-represented women lack of uniform testing

Psychological adaptation of Indian expeditioners during prolonged residence in Antarctica	Khandelwal SK, Bhatia A, Mishra AK	2017	India	Longitudinally assess the psychological adaption of Indian winter team members in Antarctica.	N/A	27 – 59 years (44.16 ± 9.34)	N/A	Indian	26	Subjects were administered seven instruments 5 times during the expedition. The questionnaires were first administered in November or December and subsequently administered in April 2008, June 2008, August 2008 and November 2008 at an interval of 2 months following the wintering season. The instruments measured cognition and memory, general psychological health and tobacco, and alcohol consumption	PGI memory scale, General health questionnaire, Hindi mental scale examination, Well-being scale, Fagerstorm test for nicotine dependence, CAGE questionnaire	Results show that each phase of Antarctic residence could be equated with a particular stage in psychological adaptation. Anxiety and insomnia peaked during the coldest period whereas depressive symptoms did not change throughout the expedition. Cognition was at its worst during the final phase of Antarctic residence. There was no third	Small sample size, possible influence of environmental issues on alcohol and tobacco consumption, focus on negative impact

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Psychological and Behavioral Changes during Confinement in a 520-Day Simulated Interplanetary Mission to Mars	Basner M, Dinges DF, Mollicone DJ, Savelev I, Ecker AJ, Di Antonio A, Jones CW, Hyder EC, Kan K, Morukov BV, Sutton JP	2014	USA	Report the behavioral and psychological effects on a 6-person multinational, culturally diverse crew comparable to space fliers, who were participating in the first high-fidelity simulated 520-day mission to Mars	N/A	27–38 years (mean age 32.0 years)	Males	3 Russians, 2 Europeans & 1 Chinese	6	Rest-activity of crewmembers was objectively measured throughout the mission with wrist-worn actigraphs. Once weekly throughout the mission crewmembers completed the Beck Depression Inventory-II (BDI-II), Profile of Moods State short form (POMS), conflict questionnaire, the Psychomotor Vigilance Test (PVT-B), and series of visual analogue scales on stress and fatigue	Actigraphy; Social Desirability Scale 17 (SDS-17); Visual Analog Scales (VAS); Profile of Mood States - Short Form (POMS-SF); Beck Depression Inventory (BDI-II); Conflict Questionnaire (CQ); Post-mission debrief interviews; Psychomotor Vigilance Test (PVT-B)	Results suggest seasonal behavioral (e.g., changes in sleep-wake behavior), psychological (e.g., depression) and cognitive performance (e.g., accuracy, speed, attention) changes	Microgravity, radiation and threat-to-life are not met; limited access to the crew before and after the 520-day mission, and thus cannot infer about their psychological status before and after the mission; medical and psychological selection and screening of the crew made by the space agency responsibl

e for each study participant, making it uncertain to what extent it was comparable; male crew; assessment of performance limited to psychomotor vigilance testing; no measure of physiological or endocrine markers of stress; no control over the other protocols that may have introduced unexplained

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Psychological Hibernation in Antarctica	Sandal GM, van deVijver FJR, Smith N	2018	International	Examine how the use of coping strategies changed over time, and the extent to which changes coincided with alterations in mood and sleep	Medical and psychiatric screening	23 – 58 years (38.3 ± 10.64) for crew 1; 22 – 51 years (34.5 ± 9.17) for crew 2	N/A	8 Italians, 6 French for crew 1; 7 Italians, 6 French for crew 2	27 (14 crew 1, 13 crew 2)	The expedition members completed a sleep diary in the first week of each month during the stay. Completion of the PANAS was scheduled every month during the stay on Concordia as well as the UCL (x9)	Utrecht Coping List (UCL), the Positive and Negative Affect Schedule (PANAS), and a structured sleep diary (bedtime, light out time, sleep onset latency, number and duration of awakenings, time of final awakening, rise time, and sleep quality)	Results suggest that negative feelings were continuously low during the entire stay at the station and did not change over time. Inversely, positive states and coping strategies fluctuated depending of time, with the worst effect during the winter. Correlations between the psychological variables and time were negative or positive across	Use of self-reports, responses may be influenced by report biases, no gender examination

												seasonability. They highlight psychological hibernation as a new coping mechanism	
Reductions in circulating endocannabinoid 2-arachidonoylglycerol levels in healthy human subjects exposed to chronic stressors	Yi B, Nichiporuk I, Nicolas M, Schneider S, Feuereck er M, Vassilieva G, Thieme D, Schelling G, Choukèr A	2016	Europe	Examine the impact of chronic exposure to isolation and confinement through monitoring psychological state, brain cortical activity	Detailed medical history and clinical examination	33 ± 6 years	Males	3 Russians, 2 Europeans & 1 Chinese	6	Subjects completed monthly the PANAS questionnaire. EEG data collection took place in a sitting position for three minutes. Participants were seated in a relaxed position, with eyes closed. Collection data periods were 360d, 410d, and 510d	Positive Affect Negative Affect Schedule (PANAS), EEG	Results suggest an impact in both psychology (e.g., positive emotions) and physiology (e.g., decreased brain cortical activities). No significant changes were reported for negative emotions	N/A

Shifts in broadband power and alpha peak frequency observed during long-term isolation	Weber J, Klein T, Abeln V	2020	International	Investigate how neural activity is altered during 120 days of isolation in a spatially confined, space-analogue environment	N/A	33.67 ± 6.41 years	3 males, 3 females	N/A	6	EEG activity was recorded at 32 scalp sites on 6 different timepoints: The first assessment day was 13 days prior to the start of the isolation period (Pre-Isolation). The second, third, fourth and fifth measurement were taken at isolation day 15, 54, 79 & 110, respectively. The last assessment was taken 7 days after participants were released from isolation (Post-Isolation)	EEG	Results show an increase cortical deactivation (e.g., reduction in broadband power and a flattening of the 1/f spectral slope, and in alpha peak frequency during isolation)	Small sample size, no control group, confounding factors exist (i.e., mood, boredom or shifts in sleep cycles)

Sleep during an Antarctic summer expedition: new light on « polar insomnia »	Pattyn N, Mairesse O, Cortoos A, Marcoen N, Neyt X, Meeusen R	2017	Belgium	Study sleep and determine circadian regulation and mood during a 4-mo Antarctic summer expedition	Medical and psychiatric examination and acclimatization training	27 – 57 years (mean age 35.0 years)	Males	N/A	21	All data collection was performed during the continuous illumination of the Antarctic summer. After an habituation night and acclimatization to the environment (3 wk), ambulatory polysomnography (PSG) was performed. An 18-h profile (saliva sampling every 2 h) of cortisol and melatonin was assessed. Mood, sleepiness, and subjective sleep quality were assessed, and the psychomotor vigilance task was administered. A group of matched controls was used	Melatonin, GammaCoat Cortisol, EEG, ECG, respiration, EMG, total sleep time (TST); sleep onset latency (SOL), wake after sleep onset; sleep efficiency (SE); %SWS of the sleep period time (SPT); %stage R sleep of the SPT and sleep stages 1 and 2 sleep (S1–S2) of the SPT; stage R latency; and SWS latency, Profile of Mood States, Karolinska Sleepiness Scale (KSS), sleep diary, Self-Assessment of Sleep and Awakening Quality Scale, Psychomotor vigilance task	Results report polar insomnia, a decrease in slow-wave sleep, and an ultradian sleep structure distortion. No significant effect on mood was found	Small samples size, no exact determination of the secretion peak for melatonin, salivary melatonin instead of urine sample, polysomnography setup with only one EEG channel, a single EMG placed on the chin (not on the leg)

Sleep patterns of crewmembers in mission IV of the Hawaii space exploration analog and simulation (HI-SEAS): a pilot study	Matsangas P, Lewis Shattuck N, Heinicke C, Dunn J	2017	International	Assess the sleep-related behaviors of crewmembers during one month of Mission IV	N/A	24 – 33 years	2 males, 3 females	N/A	4	N/A		Wrist-worn actigraphy, log	Results identified substantive individual differences in sleep-related behaviors, physical activity and exposure to light between the crewmembers.	Missing informations about participant behavioral patterns before the study, standardized mood and sleep quality questionnaire not incorporated, data collected only towards one month
Sleep Quality Changes during Overwintering at the German Antarctic Stations Neumayer II and III: The Gender Factor	Steinach M, Kohlberg E, Maggioni MA, Mendt S, Opatz O, Stahn A, Gunga HC	2016	Europe	Assess changes in sleep patterns during 13 months of overwintering at the German Stations Neumayer II and III	Medical and psychological screening and ensured that crew members were of good physical and mental health and were not taking any medication	33 years	37 males, 17 females	N/A	54	N/A		Time in bed, sleep time, sleep efficiency, number of arousals, sleep latency, sleep onset, sleep offset, and physical activity level	Results reported changes in sleep patterns. Gender modifications appears with a decrease in sleep quality for woman, despite an unchaiged physical activity.	N/A

Sleep Stability and Cognitive Function in an Arctic Martian Analogue	Gríofa MO, Blue RS, Cohen KD, O'Keeffe DT	2011	USA	Evaluate the effect of a Martian sol on the subjective and objective sleep disruption of crewmembers during a long-duration mission in a space analogue environment and the effect of such disruption on objective cognitive performance	Medical and psychological examination	N/A	4 men, 3 females	N/A	7	Sleep diary data were collected on all seven crewmembers beginning 10 nights prior to the experiment. Subjective sleep monitoring was obtained pre- and post-sleep using a questionnaire derived from the Pittsburgh Sleep Diary modified to mission-specific queries. Collection continued each night throughout the sol and during a post-Martian time period of 13 nights. The sleep diary was organized as a 12-component questionnaire. Objective measurement of circadian or sleep disruption was obtained by cardiopulmonary coupling data by means of CASPER with electrocardiogram and pulmonary data recorded by flash drive. Cardiopulmonary coupling data collection occurred in measurement blocks of 5 nights per block beginning prior to the study. Collection continued throughout the sol, implemented on	ECG (HRV, HF, LF), respiration, Pittsburgh Sleep Diary, Cardiac Adapted Sleep Parameters Electrocardiogram Recorder (CASPER), Decision Speed Test, Reaction Time Test	Results show an increase in subjective sleep and alertness. However, no significant alteration of sleep patterns was found. There was no signs of cognitive decline over the course of the mission	Small sample size, no control group, no evaluation of more complex tasks

mission day 51, and also during a post-Martian time period. Two crewmembers were recorded for each data night, with a total of four crewmembers undergoing sleep monitoring throughout the mission. Only four crewmembers underwent monitoring due to operational and equipment constraints. Cognitive data were collected on all seven crewmembers beginning 10 nights prior to the implementation of the sol, then continued each night through the sol and for a post-Mars period of 13 d. Subjects underwent two separate tests of cognitive function. For consistent data collection, tests were completed within 15 min prior to sleep and 15 min of waking

Sleep-wake differences in heart rate variability during a 105-day simulated mission to Mars	Vigo DE, Ogrinz B, Wan L, Bersenev E, Tuerlinckx F, Van Den Bergh O, Aubert AE	2012	International	Investigate whether the sleep-wake variations in the autonomic control of the heart are specifically altered by long-term confinement during the 105-day pilot study of the earth-based Mars500 project	N/A		33 ± 6 years	Males	N/A	6	Twenty-four hour Holter signals were obtained at five time points: in one day between 17 to 20 days before confinement (Pre); in one day between the 38th to the 40th day of confinement (T1); in one day between the 73th to the 76th day of confinement (T2); in one day between the 98th to the 100th day of confinement (T3); and in one day between 11 to 13 days after the end of confinement (Post). Data collection was performed regardless of day or night shift of the subject. Electrocardiogram signal was recorded	ECG, RRm, SDNN, RMSSD, HF, LF, VLF, LF/HF, TP), tdown, tup, HR, circadian rhythms	Results suggest that wake HRV showed decreased mean heart rate and increased amplitude (e.g., high frequency). Sleep HRV remained stable, instead of sleep-wake high frequency HRV differences who decreased	Small sample size (limited conclusions), determination of sleep – wake periods requires other techniques, confinement perhaps not long enough to highlight autonomic activity

Sleep, napping and alertness during an overwintering mission at Belgrano II Argentine Antarctic station	Folgueira A, Simonelli G, Plano S, Tortello C, Cuiuli JM, Blanchard A, Patagua A, Brager AJ, Capaldi VF, Aubert AE, Barbarito M, Golombek DA, Vigo DE	2019	Argentina	Assess sleep patterns and alertness in a Latin American crew during a one year overwintering mission in Antarctica and explore whether sleep-wake cycle during the year modulate possible alertness variations	Medical histories and physical examinations	34 ± 1 year	Males	Argentinian	13	Measurements were collected every other month from March to November	Blood pressure, Pittsburg Sleep Quality Index, Epworth Sleepiness Scale, sleep log (number of recorded nights, sleep onset, sleep offset, sleep duration, sleep efficiency), Psychomotor vigilance task (mean response times for all trials (MRT); the standard deviation of the response times for all trials (SRT); the fastest 10 % of response times for all trials, or optimum response domain (FRT); the slowest 10% of reciprocal response times for all	Results show that sleep duration significantly decreased during winter and a significant effect of seasonality in the association of evening alertness with sleep onset. Blood pressure did not present significant variations across time	No urban controls, no measure during December or February, only young males

trials, or lapse domain (IRT); and the percentage of response times ≥500 ms for all trials, or percentage of lapses (LRT))

Sleeping under the Ocean: Despite Total Isolation, Nuclear Submariners Maintain Their Sleep and Wake Patterns throughout Their Under Sea Mission	Trousselard M, Leger D, van Beers P, Coste O, Vicard A, Pontis J, Crosnier SN, Chennaoui M	2015	France	Assess the effects of isolation, inadequate exposure to light and specific shift work on the subjective and objective measurements of sleep and alertness of submariners	N/A	N/A	Males	N/A	19	Participants attended two polysomnographic (PSG) recordings of night sleep on Day 21 (D21) and Day 51 (D51) of the 70-day patrol; urine cortisol levels were also taken after sleep, and subjective assessments of sleep, sleepiness, mood and anxiety on D21 and D51. The light and temperature on board were also recorded. The crew was divided into three teams and submariners worked throughout the mission on a 3-day shift rotation. Sleep was scheduled in three 8-hour periods and one 4-hour additional period. The first night's recording was performed on the second day of the shift, between midnight and 8 am, the 21st day of the mission (D21) 19 days i.e., 7 shifts, after the first D2. A second assessment was performed on day 51 (D51), 10 shifts later	Buguet sleep scale, based on visual analogue scales (VAS), cortisol, Epworth sleepiness scale (ESS), French short-version of the Profile of Mood Scale (POMS), polysomnography (total sleep, period (TSP) in minutes (min), total sleep time (TST, min), sleep onset latency (SOL, min), sleep efficiency 1(SE1, percentage), sleep efficiency 2, wake after sleep onset (WASO, min)), % of sleep stages (Stage 1 and 2 = light sleep; Stage 3 = Slow wave	Results do not report sleep disorders, no modifications of feelings of fatigue, depression, anxiety or vigour. Associations between sleep and psychological variables were highlighted	Sleep patterns were only assessed twice during the mission, no baseline, sleep patterns recorded in 19 volunteer crew members and cannot confirm that this group was necessarily representative of the entire crew, REM latency and cortisol blood levels do not strictly reflect the adaptation of the

sleep (SWS); Rapid Eye Movement (REM) sleep and REM sleep latency), number of periods, average period (min), shortest period (min), longest period (min), and average intervals between SWS periods and REM periods (min)	biological clock, not able to conclude that some of submariners were more adapted to those conditions than the others

Spaceflight-Associated Brain White Matter Microstructural Changes and Intracranial Fluid Redistribution	Lee JK, Koppelmans V, Riascos RF, Hasan KM, Pasternak O, Mulavara AP, Bloomberg JJ, Seidler RD	2019	USA	Map spaceflight-induced intracranial extracellular free water shifts and to evaluate changes in brain white matter diffusion measures in astronauts	Astronaut selection	47.2 ± 1.5 years	12 males, 3 females	N/A	15 (7 subjects space shuttle mission, 8 subjects long space mission)	N/A	Diffusion magnetic resonance imaging, Sensory Organization Tests	Results reported changes in white matter structural connectivity in the cerebellum, corticospinal tract, and the superior longitudinal fasiculus. Brain changes were linked with postural balance declines.	Several timing of magnetic resonance imaging acquisition and scan sequences across patients, low spatial resolution
Specificity of Sleep–Wakefulness Cycle during a 105-Day Isolation	Kovrov GV, Rusakova IM, Shvarkov SB, Posokhova SI, Posokhova SS, Ponomarevab IP	2010	Russia	Reveal the peculiarities of the sleep–wakefulness cycle, the main mechanisms of its disturbance, and the relationship between daytime wellbeing and sleep quality during a	N/A	25 – 40 years	N/A	N/A	6	The subjects wrote a diary in the sleep–wakefulness cycle every six days. Gradual subjective adaptation observed during the experiment was recorded using subjective indices and expressed in the weakening of emotional, muscular, and intellectual tension before sleep and improvement of self-rated wellbeing in the morning. Physiological	Diary, polysomnography, electroencephalogram (EEG), electromyogram (EMG), electrooculogram (EOG), sleep stages, phases	Results suggest that the mechanisms of the arrangement of sleep stages and phases were stable before, during, and after the and that the structural organization of sleep	N/A

				105-day isolation						data were recorded in two records for each volunteer: two weeks before the beginning of isolation, two weeks after the end of isolation, two weeks before the end of isolation, and during two weeks after the end of isolation		was episodically altered	
Stress and Recovery Responses during a 105-day Ground-based Space Simulation	Nicolas M, Gushin V	2014	Europe	Analyze the time course of the psychological process of stress and recovery in six healthy male volunteers during the Mars 105 experimentation, a 105-day ground-based space analogue	Medical and psychological examination	25 – 40 years (32.7 ± 5.9)	Males	4 Russians, 1 German & 1 French	6	Psychological measures were assessed at baseline (BDC 14, BDC 7 andBDC3),at1,23,44,65, 86and99daysforthe ICE period (ICE 1, ICE 2, ICE 3, ICE 4, ICE 5 and ICE 6), and in post-ICE period at +1, +3 and +7 days after the ICE period (Post 1, Post 2 and Post 3)	Recovery–Stress Questionnaire for Athletes	Results show that environment not systematically induce stress overload and impaired psychological states	N/A

Study of individual and group affective processes in the crew of a simulated mission to Mars: Positive affectivity as a valuable indicator of changes in the crew affectivity	Šolcová I, Lačev A, Solcova I	2014	Czech Republic	Examine the ways crewmembers of a 520-day simulated spaceflight to Mars (held in the Institute for Biomedical Problems, in Moscow) experienced and regulated their moods and emotions	N/A	27 – 38 years (32.16 ± 4.99)	Males	3 Russians, 2 Europeans & 1 Chinese	6	17 measurement sessions held between 23 June 2010 and 26 October 2011. Baseline measurement took place before the start of the experiment (24 April 2010) and a follow-up measurement was performed 3 months after the termination of the experiment (25 February 2012). Semi-structured individual interviews, each lasting for approximately 1 h, were conducted 14 days following the termination of the simulation	UWIST (Mood Adjective Checklist), checklist of emotion frequency and regulation, semi-structured individual interviews	Results show different patterns of adaptation between crewmembers regarding their usual life. Crewmembers preferred to suppress and neutralize their negative emotions and express overtly only emotions with positive valence. A diminution in positive emotions suggest contrary to negative ones suggest that positive affect may reflect a	Self-report questionnaires, mall, sample, different cultural background of participants, unique duration of simulation

												more valuable changes in emotional regulation in extreme environments	
The impact of long-term confinement and exercise on central and peripheral stress markers	Jacubowski A, Abeln V, Vogt T, Yi B, Choukèr A, Fomina E, Strüder HK, Schneider S	2015	International	Investigate the effects of a prolonged isolation on stress reaction	Astronaut selection	27 – 38 years (31.3 ± 4.1)	N/A	International crew	6	Cortical activity was measured by electroencephalography (EEG) every two weeks, salivary cortisol was taken every 60 days in the morning immediately after awaking (between 7 to 8 am)	Electroencephalography (EEG), salivary cortisol	Results show a reduction of cortical activity, an increase level of cortisol that could impair performance	EEG recordings were limited to 16 electrodes, not optimal moment to collect salivary cortisol, no control group of age and sex

The NASA Twins Study: A multidimensional analysis of a year-long human spaceflight	Garrett-Bakelman FE, Darshi M, Green SJ, Gur RC, Lin L, Macias BR, McKenna MJ, Meydan C, Mishra T, Nasrini J, Piening BD, Rizzardi LF, Sharma K, Siamwala JH, Taylor L, Vitaterna MH, Afkarian M, Afshinnekoo E, Ahadi S, Ambati A, Arya M, Bezdan D, Callahan	2021	USA	Presents multidimensional description of the effects of a 340-day mission onboard the International Space Station	N/A		50 years	Males	2 American twins	2	Participants were characterized across 10 generalized biomedical modalities before (preflight), during (inflight), and after flight (postflight) for a total of 25 months	10 cognitive tests (motor praxis, visual object learning, fractal 2-back, abstract matching, line orientation, emotion recognition, matrix reasoning, digit symbol substitution, balloon analog risk, and psychomotor vigilance), vascular and ocular measures by ultrasound and optical coherence tomography, respectively,	Significant cardiovascular, neuro-ocular and cognitive function changes occurred after one year in space. The return phase is considered as a real challenge for readaptation	Small samples

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The tougher the environment, the harder the adaptation? A psychological point of view in extreme situations	Nicolas M, Martinent G, Suedfeld P, Palinkas L, Bachelard C, Gaudino M	2021	International	Investigate the evolution of psychological adaptation process over a one-year period in two polar stations and the effects of percived control on the dynamics of psychological adaptation process experienced by winterers	Medical and psychological screening based on educational, professional, medical, psychological tests and an interview	21 – 51 years (33.34 ± 11.90) (Amsterdam station), 20 – 54 years (36.48 ± 12.80) (Concordia)	17 men, 5 women (Amsterdam station), 34 men, 5 women (Concordia)	N/A	61 (22 Amsterdam station, 39 Concordia)	Subjects completed questionnaires the first day on the station, at five months, eight months and one year	ICE-Q questionnaire, Perceived Mastery Scale were recorded at both Amsterdam station and Concordia	Results reported different psychological adaptation processes according to the polar station with a linear decrease in emotional, social component at Concordia and in physical component at Amstardam station, a quadratic decrease in job demand with more stable values at the end of winter. They show a positive association between perceived control and levels of emotional,	Small sample size, heterogeneityof crews, measures not generalized

												social and physical adaptation at the beginning of the winter fot both stations; and between percieved control and emotional component only at Concordia	
Time Effects, Displacement, and Leadership Roles on a Lunar Space Station Analogue	Wang Y, Wu R	2015	China	Identify possible changes in the emotional states, group dynamics, displacement, and leadership of crewmembers during an 80-d isolation period	N/A	N/A	2 males and 2 females	4 Chinese	4	All of the crewmembers completed a Profile of Mood States (POMS) questionnaire every week and two group climate scales questionnaires every 2 wk; specifically, a group environment scale and a work environment scale. They assigned to tasks every day to simulate the astronauts' schedule	Profile of Mood States (POMS), Group Environment Scale (GES), and the Work Environment Scale (WES)	Results suggest that time effects, displacement, can influence mood states in crewmembers. Fatigue was particularly increased during the first phase of the mission. There was not the evidence of a third-	Small sample size, data from outside personnel were not available

											quarter phenomenon	
Two year follow-up study of stressors and occupational stress in submariners	Brasher KS, Sparshott KF, Weir AB, Day AJ, Bridger RS	2012	England	Compare stress prevalence in submariners with matched controls and identify predictors of occupational stress in submariners over a 2 year follow-up period	N/A	N/A	N/A	N/A	288 (144 submariners, 144 general service controls)	All participants were respondents to a questionnaire assessing work demands and stress at time point 1 and to a follow-up stress questionnaire 2 years later at time point 2. Stress was measured at time points 1 and 2. The time point 1 questionnaire measured perceived occupational stressors	Work andWell-Being Questionnaire, GHQ-12	No differences between submariners and their surface fleet counterparts in the prevalence of occupational stress. Nevertheless, different predictors for the development of stress were found between the two groups. For submariners, over-commitment and rank were the	Occupational stressors not assessed at time point 2, relatively low response rate at time point 1 from submariners

												main predictors instead of controls, with the length of service, the body mass index and the physical work	
Vegetative regulation of blood circulation in the Martian crew individuals in the Mars 500 project to Mars	Bersenev EY, Rusanov VB, Chernikova AG	2013	Russia	Evaluate the vegetative regulation of blood circulation and assess individual health risks under conditions of the 520 day isolation	N/A	32 ± 3.7 years	Males	International crew	6	Studies were conducted before starting the isolation and every month in the morning hours. The experiment covered 4 main stages as listed below: background studies, the beginning of the isolation (June to November 2010), preparation and implementation of « landing to Mars », dividing of the crew into groups (December 2010 to February 2011), the return journey to Earth, finishing of the experiment (March to November 2011). During the experiment, two off-nominal situations were simulated (1 - 2 December 2010: imitation of an onboard	Ratio between the functional reserves (FR) and the degree of tension (DT), state of physiological norm, the prenosological state, the premorbid state and the pathological state, HR, SI, pNN50, SDNN, HF %, VLF %, HF, LF %. The activity of the centers of the blood vessel tonicity regulation (LF %) was stepped down, that	HRV parameters highlight (i.e., HR, pNN50, SI) the multistage nature of the process of a long-term adaptation and its relevance to assess the functional state and the adaptability of a human under changed conditions. No serious changes in	Small samples

fire emergency, 18-25 April 2011: simulated loss of communication with the Earth with an absolutely autonomous space flight).	resulted likely from the reduced physical activity of the crew	the functional state are found, and the adaptive reactions of the crew individuals have been adequate mos of the time. The functional state throughout the period of the survey has been found to be within the physiological norm. Data reveal individual features of adaptation to the experiment environment

Work content influences on cognitive task load, emotional state and performance during a simulated 520-days' Mars mission	Cohen I, den Braber N, Smets NJJM, van Diggelen J, Brinkman W-P, Neerincx MA	2016	Netherlands	Study the influences from different work contents on core variables of the COPE model (i.e. cognitive task load and emotional state) and the prediction of task performance based on these variables	N/A	25 – 50 years (mean age 32.3 years)	Males	N/A	6	The participants were divided into two groups of three participants. These were also the groups in which the tasks were performed. For practical reasons, one group consisted of the English speaking participants and one group consisted of the Russian speaking participants. Every other week, a session started for half an hour. In every session three tasks were executed: a learning activity, called Collaborative Trainer (COLT); a negotiation game, named Colored Trails (CT); and an entertainment game, called Lunar Lander (LL). COLT and CT are multi-user (group) tasks, whereas LL is a single user game. The task starts with an emotional state questionnaire (time = T0), followed by the tasks. After the task was completed an emotional state and a cognitive task load questionnaire followed (time = T1). For the Lunar Lander and Colored Trails task, the procedure stops	Collaborative Trainer (COLT); a negotiation game, named Colored Trails (CT); and an entertainment game, called Lunar Lander (LL). COLT and CT are multi-user (group) tasks, whereas LL is a single-user game, Emotional state (ES) & cognitive task load (CTL),	Result show significant differences between cognitive task load and emotional state levels when work content varied. There is an association between cognitive, affective factors and task performance	Small sample size, emotional state and cognitive task load measures were all subjectively measured, COPE model looks at the current state of a person when engaged in a stressful task, COPE factors did not lead to a significant regression model

there. The COLT sequence continued with an examination part, followed by a teacher/student questionnaire and a second emotional state and cognitive task load questionnaire (time = T2). The whole simulated Mars mission lasted for 520 days and was divided into four different phases. The simulated Mars landing divided the mission into two halve. Both halves were divided equally, resulting in four phases. The first phase (session 1–9, week 1 to week 18) and the second phase (session 10–19, week 19–38) were before the Mars landing, and phase three (session 20–29, week 39 to week 58) and four (session 30–38, week 59) were after the Mars landing

3.6.1. Types

All the 69 publications were quantitative studies. Experiments in the space environment were, however, under-represented – only eleven studies took place during a spaceflight. Twenty-seven focused on polar environments: two expeditions, two in the Artic polar desert, four at the Concordia station; one at both Concordia and the Durmont d'Urville station (DDU), one at both Concordia and the German Neumayer III station, one at both Concordia and Amsterdam station, one at the DDU, one at both DDU and Kerguelen station, one at the Syowa Station, one at the Akademik Vernadsky station, four at the Maitri station, two at the Belgrano II station, one at the Belgian station, one study at both the Mc Murdo and the South Pole stations, one study at the Zhongshan station, one study at both the Chinese Great Wall and Zhongshan stations, one study at both the German Neumayer II and III stations, and one study at the German Neumayer III station. Twenty-nine investigated spaceflight simulation, broken down as follows: the Russian Academy of Sciences' Institute of Biomedical Problems (21 studies), the HERA facility (two studies), the Mars desert research station (one study), the Lunar Palace (two studies), the NASA Extreme Environment Mission Operations (NEEMO) (one study), the Hawaii Space Exploration Analog and Simulation (HI-SEAS) (one study), and the Controlled Ecological Life Support System (CELSS) (one study). The activities carried out during space simulations have the will to reproduce the typical days of the astronauts on board the ISS as well as the living conditions. Also, they have an important margin of maneuver allowing to challenge the mission (e.g., extension of the mission duration) (Hao et al., 2020).

Two studies were run in a submarine environment (Brasher et al., 2012; Trousselard et al., 2015). Analogs such as bed-rest, dry immersion, parabolic flights, and OPEX studies were considered as out of scope and excluded from this review.

3.6.2. Time spent in the environment

The length of the study in the ICE/EUE varied from 15 days to 17 months, broken down as follows: four studies lasted about two weeks, 12 between one to four months, nine studies lasted approximatively six months, three lasted one month, 23 lasted around one year, and 12 studies extended over 18 months. In other cases, either the duration was not reported (two studies), or several studies were run over different periods of time (4 studies).

3.6.3. Fidelity of analogs to the vacuum of space

Studies were evaluated with respect to their fidelity to the space environment. Ratings ranged from five to 13 (i.e., see Methodological quality and level of evidence in Methods section for further details). Thirty-three were rated as High (10−13), twenty-seven as Medium (7−9), and nine as Low (4−6) fidelity. The high-fidelity studies were broken down as follows: spaceflight (eleven studies), spaceflight simulation (13 studies were dedicated to the Mars 500 experiment), one from the CELSS platform, one from the HERA facility, one from the Lunar Palace, one from the Scientific International Research In a Unique terrestrial Station program (SIRIUS); one from the HI-SEAS facility; and four from Antarctica.

Medium fidelity studies were broken down into: spaceflight simulation (seven were dedicated to the Mars 105 experiment), one study at the Lunar Palace, one study at the HERA facility, one at the Mars desert research station, one at the NEEMO facility, and various Antarctic stations (16 studies). Low fidelity studies examined submarine patrols (three), and Antarctic stations (six).

Space studies are complex to implement. There are very expensive to run, require a high degree of technology, and space agencies receive many requests, but only select a few research teams. Pagel and Choukèr (2016) underline that analogs offer a standardized, high-fidelity experimental framework, and a real expedition environment. They make it possible to simultaneously collect data from more subjects, using a wider range of methods, for variable durations, and in controlled environmental conditions. These experiments offer unique ecological conditions to explore the nature of human adaptation in a clinical context. Most analog studies ran for about one year in ICE/EUE in Antarctica. Other representative studies were run in a spaceflight simulation; however, it should be noted that there is a high degree of heterogeneity between these environments.

4. Discussion

Humanity is one step closer to returning to the Moon and embarking on a journey to Mars. The progress that has taken place over the past decade is unprecedented. Advanced life-support technology has allowed us to explore places where we could not have survived before. The three objectives of this systematic review enriches knowledge in the field of human adaptation to the challenges of space missions and travel by (1) summarizing the existing literature on the impact of professional ICE/EUE on human adaptation from a broader studied framework (i.e., physiological, biological, neuroscience, cognitive, and psychological), (2) describing the identified psycho-cognitive processes and neural mechanisms developed by professionals to cope in these exceptional environments, and (3) exploring the differences and similarities between space analogs (i.e., represented by ICE and EUE environments), in terms of their impacts on human adaptability. Humanity is one step closer to returning to the Moon and embarking on a journey to Mars. The progress that has taken place over the past decade is unprecedented. Advanced life-support technology has allowed us to explore places where we could not have survived before. The need to sustain life in space has presented many unique challenges to research, since the dawn of the space age more than 60 years ago. However, many challenges remain before we can preserve life beyond Earth.

4.1. What analogs?

Our analysis of the environments included in this review reveals that studies in space are underrepresented. Analog environments are, thus, a real pathway to carrying out research that is complex to undertake during a space flight. Our review also highlights that simulation studies appear to be most faithful to the conditions found in long-duration missions, followed by Antarctic wintering. However, although simulations can closely model the conditions that crews on future exploratory missions might experience, evacuation is still possible. Thus, the crew can keep a level of control over the environment. It is always possible to be extracted from the mission within a very reasonable time. On the other hand, polar environments provide similar conditions to establishing a base on Mars or the Moon. Rescue and evacuation are very complicated, if not impossible, during the winter months, and dependent on the station’s location. Antarctica cannot be accessed every month of the year due to the formation of ice blocks.

The rotations to bring equipment and overwinterers take place between October and March of each year. On site, the access to the different stations can quickly become perilous if the weather conditions are not favorable. Thus, the crews are entirely autonomous. Emergencies cannot be rescued before several hours, days, or even no one can be rescued. Characteristics of polar stations are very different, depending on their geographical position and altitude, which ranges from 100 m to 3 233 m. Different studies reported results from polar stations at sea level (Bhattacharyya et al., 2008, Khandelwal et al., 2017; Strewe et al., 2018; Tortello et al., 2020). Thus, in terms of mission length, space simulations have lasted the longest with the Mars 500 mission (Basner et al., 2013; Basner et al., 2014; Bersenev et al., 2013; Cohen et al., 2016; Jacubowski et al., 2015; Sikl et al., 2013; Šolcová et al., 2014; Vigo et al., 2013; Yi et al., 2014; Yi et al., 2016; Wang et al., 2014; Zavalko et al., 2013). Polar environments are predominantly described by day and night periods, as well as frequent station isolation during winter months, making crews fully self-sufficient even in emergencies. In this, they are perfect analogues to future long space missions. For all that a station does not experience polar day (Chen et al., 2016a).

Another consideration is that the population included in such studies is mostly older than other ICE/EUE, and crew selection methods differ. Finally, although some parallels can be drawn, Antarctica does not replicate the weightlessness and radiation that space travelers may experience in space. This heterogeneity necessarily impacts the variables studied and raises questions about the generalizability of results. It is essential to be able to homogenize all the measurements collected within these environments. This work has already begun in the Antarctic research bases (Van Ombergen et al., 2021). As space travel continues to expand, crews will face new, and increasing challenges (Binsted et al., 2010; Engel, 2019; Orasanu & Lieberman, 2011; Palinkas, 2000; Shepanek, 2005). Given the impossibility of being evacuated or of receiving material assistance from outside, the crew can only rely on its own resources, hence the issues related to crews' selection and training.

Drawing upon the work of Bartone et al. (2018), our analysis shows that studies onboard submarines are least representative of the space environment these last years, notably because of the shorter mission duration and larger crew size. However, the stressors encountered during a patrol are the most similar to those encountered during space missions (Crosnier, 2014; Ferragu, 2019; Lafontaine, 2019; Lefranc et al., 2021; UK report, 2019). In this respect, they may be considered as the best analog (Orasanu & Lieberman, 2011). To provide clear guidelines, it is necessary to define a list of environments suitable for studying stressors involved for future space missions. Initially, space analog missions were developed based on the methodology applied for orbital spaceflights. Consequently, it seems necessary to re-categorize analogs according to new criterias that consider environmental constraints (e.g., environmental factors, characteristics specific to space), operational constraints (e.g., workload, crew composition, size, mission duration, specific tasks performed during the mission), and stressors (e.g., temporal, physico-psychological, social, and post-mission factors). The most complex constraints to measure are the temporal aspect of the mission, the distance from planet Earth, the confinement in a restricted space, the crew life and the management of the permanent danger of death. It is difficult to find a place where all these characteristics can be combined with the impact of the space environment on the human body. Today, analogue environments allow some of these characteristics to be studied separately. Nevertheless, there remain questions on the cumulative effect of all these elements. This should not be ignored, as it is precisely this cumulative effect that can lead to the individual's resources being exceeded and to a slide towards a state of chronic stress that is deleterious to health. In addition to these aspects, it also raises the question of crew selection. As long as we will be unable to define the real impact (i.e., in its global perspective) of future missions, it will not be possible to highlight the type of profile to be recruited (i.e., depending on the type of resources to be deployed to adapt). A necessary and valuable part of the development of future space missions would be long-term spatial simulations that consider the full range of cumulative effects found in ecological environments. Analogs make it possible to work with larger sample sizes, identify characteristics specific to each environment, and observe their impacts on behavior and performance (Palinkas, 2000; Shepanek, 2005). Future space exploration will be very different to current ISS missions, and professionals will need to adapt to these new objectives. A reflexive work on these issues seems essential to identify the future space analogues. A summary of the results is highlight Fig. 2.

Figure 2

An overview of findings compiled in the review

4.2. Impact of extremes on the human being

Our review highlighted significant inter-individual variability. Regardless of the field of study, results are mixed (Basner et al., 2014; Clément et al., 2020; Flynn, 2005, Kanas et al., 2013; Kim et al., 2018b; Oluwafemi et al., 2021; Pagel & Choukèr, 2016; Palinkas et al., 2000b; Strangman et al., 2014; Zimmer et al., 2013). Some find an alteration in performance, psychological disorders, and sensory and physiological changes, while others find no change, or even improvements. These modifications are not systematically independent of the phase of the mission, illustrated by the so-called 'wintering' syndrome, or the third-quarter phenomenon. Palinkas and Suedfeld (2008) argue that this is due to psychosocial, rather than environmental factors, and that it is independent of the duration of the expedition. There is no evidence of a temporal effect because results are inconclusive. They highlight a cumulative effect to environment exposure involving both temporal and seasonal aspects. A review by Patel et al. (2020) evaluated the evidence regarding a third-quarter phenomenon. They only identified a significant effect for Adjustment, which reflects individual morale. Also, some of the reactions appear to be related to prolonged isolation in extreme environments (Cunha et al., 2021). Although these symptoms are frequently reported, they are rarely treated. Palinkas et al. (2008)

related them to the cold and psychological stressors of living in the environment. Mullin (1960) argued that cold, danger, and hardship are not major stressors. Overall, the third-quarter phenomenon appears to be associated to emotional, fatigue, social, cognitive concerns and dependent of the isolation period rather than mission timeline. Nevertheless, most of studies do not report any sign of third-quarter phenomenon. This appears to be due to environmental factors (i.e., third-quarter phenomenon reported most frequently in Antractic bases) and interindividual variability. Thus, there is a need to conduct studies that explore the *in situ* impact of the evolution of the different measures through different specific times (e.g., weekly, monthly, semester, quarterly). This depends on the specificities of the mission and must be adapted to these needs. Isolation and confinement are both of far greater concern (Palinkas, 1991), and tend to increase over time (Bhargava, 2000).

Results of this review suggests that the individuals in tomorrow's missions will have the necessary background to carry out the mission they are given. Professionals in the ICE/EUE environment are adjusting to survive the first few weeks in the new environment to potentially acclimatize to the new time and environmental space they are dealing with. There are no major events to report. Nothing that directly jeopardizes an individual's life. According to the transactional model of the stress episode established by Lassarre (2002), a stress episode is structured according to three concepts: the situation (i.e., a state of stress arises when an individual is faced with an issue for which he or she must estimate gains and losses), the transactional process (i.e., the emotional and cognitive evaluation of a situation), and the stressor (i.e., emotional and cognitive evaluation of a situation in relation to its constraints and resources, the issue at stake, the magnitude and difficulty of the task to be accomplished) and the action (i.e., responding to the issue at stake in the situation in order to put an end to the stress episode through action or inaction). A stress episode is delimited by a temporal space during which individuals sometimes anticipate and sometimes feedback. Acclimatization to the environment and ultimately adaptation in the broad sense is the result of a process of negotiation leading to a compromise between individual needs and environmental demands. Depending on what is at stake in the situation, the response may differ. Thus, each individual in an ICE/EUE environment goes through a set of specific processes to respond to environmental signals. The latter induce phenotypic changes that can last for a long or short time. This will depend on the resource capacity of the individuals. In this context, it seems difficult to influence the level of environmental demands. Neither is their level of severity flexible. The environment, due to the nature of the risks to which it exposes crews, is very demanding, especially in the space environment. Consequently, it seems relevant to operate on the resources to an individual with a quintuple temporality (i.e., long before, pre in situ, in situ, post in situ and long after). The targets are both inter-individual (e.g., emotional regulation strategies, sleep management, physical activity) and intra-individual (e.g., group cohesion, strengthening the link with the Earth). The demand-resource model developed by a research team (Bakker & Demerouti, 2007; Demerouti et al., 2019) highlights the relationship between the demand inherent in work activities and the perceived resources available for them. While environmental demand affects the health of individuals, resources are dependent on the level of motivation predictive of engagement and performance. This is where the challenge of selection arises, with profiles that can endure the challenges arising from the mission and the environment, but also from the values attached to the mission they have to accomplish, and which give meaning to their lives. This is less apparent in polar environments, with more frequent reports of psychological disorders. In the other environments, variations in mood and sleep are observed instead. A review by Zimmer et al. (2013) highlights that the psychological and physical health of crews can be significantly affected in both space and analog environments. Psychological factors may have played a role in three evacuations from the Russian space station (Flynn, 2005). Also, astronauts seem to experience psychological issues throughout a spaceflight (Bettiol et al., 2018; Nicogossian et al., 2016). Both environments' and internal' stressors are reported to be at the root of psychological problems experienced both during and after long-duration space travel (Marazziti et al., 2021). Depressive and anxious symptoms were reported in Mars 500 simulation mission (Basner et al., 2014), as well as in polar stations (Premkumar et al., 2013; Strewe et al., 2018). Palinkas and Suedfeld (2008) reported that insomnia, irritability and distraction were the most common symptoms. Also, mood disorders were highlighted in Mars 500 mission, with specific time report (Basner et al., 2014; Gemignani et al., 2014; Šolcová et al., 2014; Wang et al., 2014) and a decrease in emotional regulation (Šolcová et al., 2014; Yi et al., 2016). Stress levels were mitigated. Studies reported high levels of stress in space (Barger et al., 2014), simulations space missions (Basner et al., 2014; Jacubowski et al., 2015; Wang et al., 2014; Yi et al., 2014; Yuan et al., 2019), or in polar stations (Binsted et al., 2010; Moraes, 2020; Nicolas et al., 2015). Others tend to reach casual rates (Nicolas & Gushin, 2014; Strewe et al., 2018). During a simulated Mars expedition, crew reported subjective stress rating, despite no significance on cortisol level (Groemer et al., 2010). Nevertheless, several somatic symptoms associated with stress were reported (Kanas et al., 2013; Palinkas & Suedfeld, 2008; Yuan et al., 2019). Most of the findings were reported by space simulation missions and polar winterers. Astronauts and submariners are populations trained and selected for their stress management. This may be one reason why this issue is not highlighted in the literature.

Sleep disorders appear to have the most negative impact. Among space travelers, restricted sleep is associated with abrupt changes in the sleep/wake schedule, lack of a 24-hour light–dark cycle, high workload, and physical stress (Flynn-Evans et al., 2015). Poor sleep has been found to be one of the main factors influencing neuropsychological changes (Kanas, 1997), although hypnotics may help (Barger et al., 2014; Basner et al., 2015). Space travelers sleep, on average, six hours per night, a level that is considered as chronic deprivation (Orasanu & Lieberman, 2011). However, sleep alone may not constitute a factor that decreases performance (Moore et al., 2019). Sleep is also impacted in space analogs in which fatigue was found to be significantly higher (Basner et al., 2013; Basner et al., 2015; Wang & Wu, 2015; Zavalko et al., 2013), but not necessarily consistent toward the literature (Chen et al., 2016a; Gemignani et al., 2014; Groemer et al., 2010; Matsangas et al., 2017; Pattyn et al., 2017; Trousselard et al., 2015; Wang & Wu, 2015; Yi et al., 2014). The latter has major implications for its close links with cognitive performance. The results are mixed and seem to be specific to the environments and potentially the tests used. The results are mixed and appear to be environment and potentially test specific. Both the spaceflight and analog literature report mixed results regarding cognitive performance in ICE/EUE (Pagel & Choukèr, 2016; Strangman et al., 2016). Negative impacts have been identified for high-level cognitive functions, which, along with reduced productivity and alertness, can have catastrophic repercussions for the survival of the crew. A study of a 340-day mission on the ISS found negative effects on post-flight cognitive performance (Garrett-Bakelman, 2019). While some studies find alterations in performance in perceptual-motor and attentional tasks, others do not report a decrease in executive functions (e.g., memory, reasoning, mental arithmetic) (Kanas et al., 2013; Strangman et al., 2014). Thus, least consensus is found (Basner et al., 2015; Derayapa, 1971; Rivolier, 1997). For example, Newman and Lathan (1999) found, using the Fittsberg experimental paradigm, a significant decrement in motor, but not cognitive performance. Manzey et al. (1993) reported similar results. One hypothesis regarding these mixed results is the use of inappropriate tools to detect changes (Barkaszi, 2016). In this context, Basner et al. (2015) developed a battery of 10 cognitive tests to meet NASA's needs. However, literature point out a significant learning effect on cognitive tasks during spaceflight (Basner et al., 2015; Roberts et al., 2019; Strangman et al., 2014). Another factor underlying this disparity in outcomes could be the adaptation process itself. Strategies and resources for coping with stress are not equally distributed in a social group and identifying successful adaptation will have benefits for future experiments, regardless of the environment (Palinkas, 1992).

Physiological, vestibular and somatosensory impact seem to be inherent to space or confined environments. Physiological (Farrace et al., 2003; Demontis et al., 2017; Garrett-Bakelman et al., 2019; Hughson et al., 2018; Kim et al., 2018b; Moraes et al., 2020; Otsuka et al., 2016; Patel, 2020; Wan et al., 2011) and brain (Angeloni & Demontis, 2020; Schneider et al., 2012; Stahn et al., 2019; Van Ombergen et al., 2017a; Van Ombergen et al., 2017b) modifications have also been observed. Specific cardiovascular reactions occur in long space mission (Garrett-Bakelman et al., 2019), long space mission simulations (Bersenev et al., 2013) and ice desert (Gríofa et al., 2011; Moraes et al., 2020). A review by Van Ombergen et al. (2021) examined the results of several years of research at the Antarctic Concordia station. These studies showed a periodic breathing pattern during wintering among the crew. This pattern dominated for most of the night and was associated with an increase in apneic or hyperventilating events, which continuously exceeded the acceptable clinical threshold. During one mission, an increase in obstructive breathing events was also noted toward the end of the stay. However, oxygen deficiency did not induce a clinical increase in acute mountain sickness symptoms during the first three weeks after arrival, nor did it induce venous thrombosis. These results suggest that any effects are heavily influenced by, and dependent on the characteristics and severity of the environment. Moreover, a link between anxiety and vestibular disturbances is suggest via the vestibulocortical hemisphere (Clément et al., 2020). Specifically, anxiety levels during the mission appear to be lower among right hemisphere-dominant individuals (Clément et al., 2020).

During a prolonged stay in space, vestibular and somatosensory systems are also modified (Bock et al., 2001; Demontis et al., 2017; Hallgren et al., 2016; Harris et al., 2010; Lackner, 1993; Roberts et al., 2019; Stahn & Kühn, 2021; Wood et al., 2015). Sensory inputs are affected by the linear acceleration of stimuli reaching the otolith receptors, which are essential to spatial orientation on Earth. This, in turn, impacts balance, walking speed, and head-trunk coordination (Black et al., 1995; Glasauer et al., 1995; Reschke et al., 1994). Black et al. (1995) identified a change in somatosensory and visual orientation upon return to Earth. A review by Clément et al. (2020) reports that space travelers have altered assessments of the volume, depth, and height of the habitat in which they are operating, along with distances. Pagel and Choukèr (2016) also cite a study which reports that the Hoffman reflex, considered as a measure of changes in otolith-spinal reflexes, decreased during the mission, without being significant compared to pre-mission measures. More recently, Stahn and Kühn (2021) identified neurovestibular impairment in, for example, manual dexterity, motion perception, orientation, distance estimation, rotational sensation, head-trunk coordination, along with ataxia, hypo or hypertonia, excessive body weight, and motion sickness. They suggest that complex tasks involving the encoding, processing, storage, and retrieval of visuospatial information may be particularly vulnerable. The authors highlight the essential role of the entorhinal cortex when exploring unknown terrain, navigating new planets, and performing complex operational visuospatial tasks. The hippocampus, which is vulnerable to environmental stressors, is also thought to play a fundamental role in complex spatial navigation. Few information is available on the sensory impact of ICE/EUE, where the monotony is profound. Moderate, reversible changes in visual function have been shown both in studies in the polar environment, due to altitude (Barabasz & Barabasz, 1986; Bosch et al., 2010; Guly, 2012b; Leach, 2016; Salam, 2020; Varyvonchyk et al., 2014) and in space, due to the movement of fluids to the upper part of the body (Lee et al., 2018; Mader et al., 2011; Patel et al., 2020; Zhang & Hargens, 2018). Olfactory and gustatory senses can also be disturbed during a stay in space (Leach, 2016; Newberg, 1994; Olabi et al., 2002), and increased sensitivity to sound was reported during the Russian Salyut 6 and 7 missions (Kelly & Kanas, 1992).

Moreover, an important component of the future space missions relates to the return. Some authors underline that post-mission impacts are an important risk in future space missions (Stahn & Kühn, 2021). A few studies in ICE/EUE have reported a link between performance and a lack of recovery (Nicolas et al., 2015; Pagel & Choukèr, 2016). Nevertheless, this is a crucial time point to truly assess, understand the impact of these stays on humans and their interactions with the milieu at all levels (i.e., temporal, psychiatric, psychologic, cognitive, physiologic, neurophysiologic, and somatosensory factors). The literature report various impact from several weeks to years after the end of the mission (Garrett-Bakelman et al., 2019; Liu et al., 2015; Nicogossian et al., 2016; Strangman et al., 2014; Yi et al., 2015). These ones include psychiatric and psychological disorders, physiological modifications, proprioceptive and sensory decrements, familial issues (Bloomberg et al., 2015a; Bloomberg et al., 2015b; Garrett-Bakelman et al., 2019; Kanas et al., 2013; Stahn & Kühn, 2021; Strangman et al., 2014; Yi et al., 2015; Wood et al., 2015). Preparing the return from the mission will thus be a crucial point to ensure that it goes as well as possible both psychologically and physically. The plastic capacity of the brain has been widely demonstrated and allows adaptation to a new environment. However, the process of returning can be complex and confronts the individual with a new foreign environment. The quality of the feedback depends on the state of health in which the individual leaves the ICE/EUE environment. Each study conducted in these environments should systematically evaluate the recovery of the crews. This fact constitutes a major concern for future long space missions. Lack of recovery can lead to psychological and behavioral disorders and compromise an individual's ability to adapt to environmental stress.

4.3. Adaptation in space and analogs

At present, our results do not allow us to highlight the psycho-cognitive mechanisms underlying adaptation. One of the crucial points is that the difference between the analogues being so important between certain studies, it is not possible to generalize the results and clearly discriminate responses in terms adaptation (i.e., evidenced through acclimatization process). Further studies need to better describe the human responses in the time of the mission; this will be relevant for identify physiological, biological and/or psychocognitive variables of interest for health monitoring during long mission. Indeed, the studies are often heterogeneous, and the observed phenomena mixed or even contradictory. There are as many possible strategies as there are environments and individuals. Adaptation involves multidimensional, complex, and several dynamic processes (Nicolas et al., 2021). Nevertheless, some categories appear: coping and defense mechanism toward a cognitive regulation; behavioral toward crewmembers, or auto directed; nonlinear over time with stages (e.g., beginning, middle, several weeks before the end, return) as the mission progress; and salutogenic strategies toward positive outcomes. Individuals in space and analogs are an unusual population. They are resourceful, able to manage stress, and adapt (Antonovsky, 1987; Barkaszi et al., 2016; Sandal et al., 2006; Nicolas et al., 2022). Palinkas (1990) reported that people who have spent time in these extreme environments have fewer pathologies than the general population: 73% fewer admissions for neoplasms, 60% fewer for endocrine, nutritional, and metabolic diseases, and 44% fewer for musculoskeletal diseases. Such individuals were generally highly stress-resistant and predisposed to adaptation (Weiss et al., 2000). Another aspect is mindful disposition, where a recent study highlighted its benefits on submariners' ability to cope with confinement during a nuclear submarine patrol (Aufauvre-Poupon et al., 2021). Cette capacité nommée *mindfulness* désigne un trait stable de la personnalité, un état psychologique transitoire, et un type d'intervention. Rohrer (1961) highlighted three stages of adjustment among individuals in ICE/EUE: (1) initial anxiety at the beginning of the mission; (2) mid-mission monotony and depression as the routine is established; and (3) late-mission euphoria or hostility as the end is anticipated. These modifications are particularly apparent during the third quarter, even if the existence of the third-quarter phenomenon remains disputed.

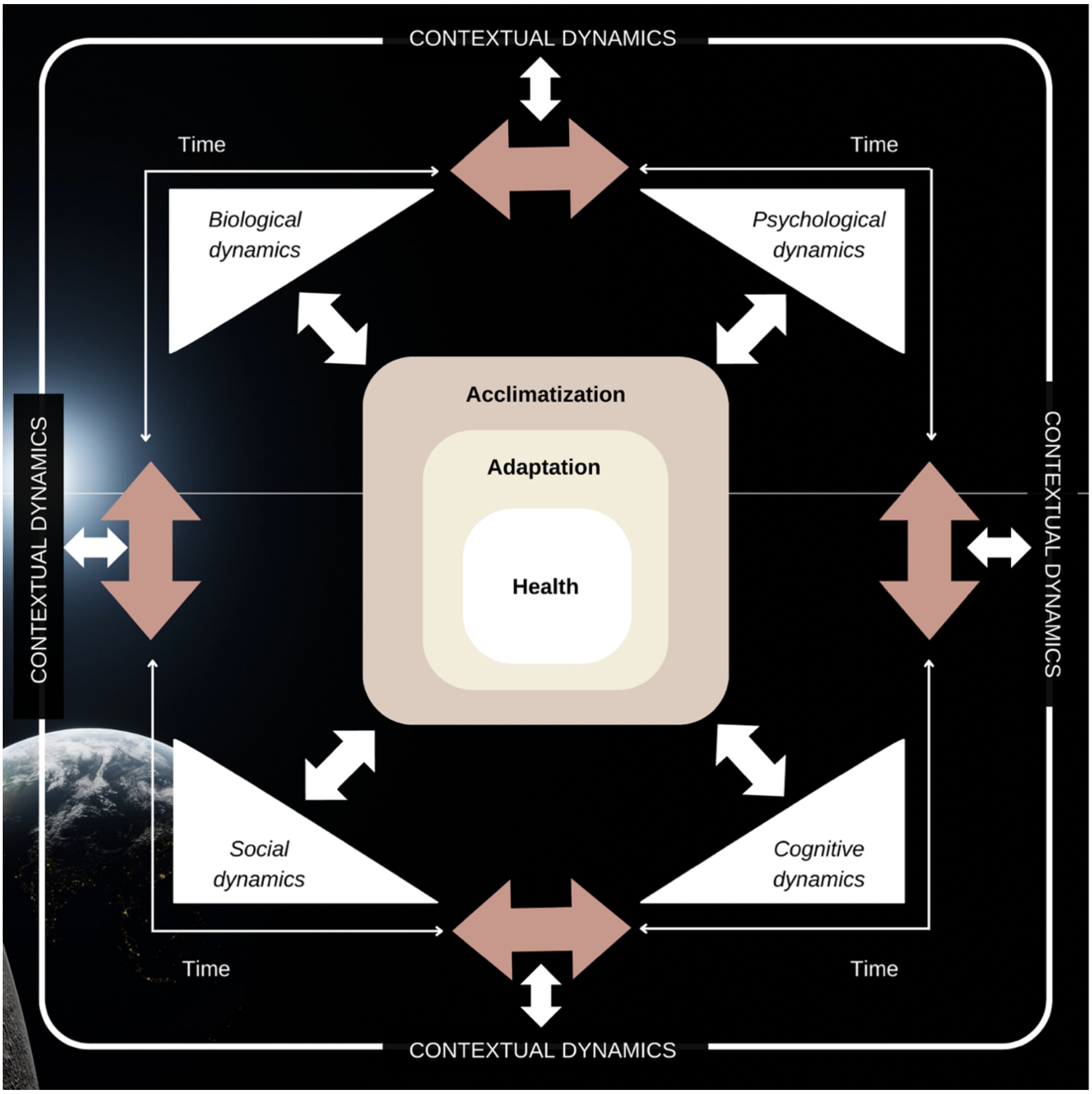
The strategies employed to cope with environmental stress are highly individual. Each person finds a way to balance the demands of the environment, and the resources available to maintain their ability to operate. This model is similar to the stress-adaptation paradigm developed by Selye, in which the capacity to adapt successfully decreases as time passes (Selye, 1956). In a review, Zimmer et al. (2013) showed that the impact of stress factors could affect individual performance during Antarctic missions (i.e., cognitive impairment, hormonal alterations, stress, fatigue, adaptation difficulties). On the contrary, Palinkas and Suedfeld (2008) suggests that rates of stress may decrease, giving a way to adaptation. In another study, Palinkas and Suedfeld (2021) argue that the characteristic symptoms of polar T3 syndrome are merely a physiological adaptation to prolonged exposure to the extreme temperatures and the lack of light that occur during winter. Finally, four factors have been identified as key to successfully maintaining space travelers' performance during long missions: psychological adaptation; the human-system interface; sleep and circadian function; and behavioral health (Flynn, 2005). Studies of space missions have highlighted strained relations between the crew and the control center. Kanas et al. (2009) argue that this strategy of transferring conflict to the outside world is a way to vent negative emotions. They point out that it is undesirable because of an increased risk of blocked emotions, territorial behavior, and poor group cohesion, which are crucial factors for the success of the mission. Rohrer (1961) described three stages in an individual's reaction to conditions in ICE/EUE. The first stage, initial anxiety (related to the perceived danger), occurs at the beginning of the mission. The second, depression and boredom (due to the routine), increase gradually as the mission progresses. The final stage, terminal euphoria (i.e., childlike, hypomanic and aggressive behavior), is a period of anticipation as the end of the mission approaches (Kanas, 1987). At the same time, the mechanisms that individuals use to cope with these stressors can have a significant influence on their ability to maintain their health and professional activities during the mission. In this context, the coping framework (Lazarus & Folkman, 1984) identifies two, well-known strategies: problem-focused and emotion-oriented. Both are observed in extreme environments (Palinkas & Suedfeld, 2008; Suedfeld, 2001; Suedfeld, 2005), and tend to evolve as time passes (Nicolas et al., 2013; Palinkas, 1989). More recently, Nicolas et al. (2021) highlighted that perceived control towards the environment constraint impact adaptation processes with an increase of emotional and physical component. Both stress and recovery responses seem correlated with the latitude of the polar station, and thus with the harsh of the environment (Nicolas et al., 2022).

Therefore, dynamic interpersonal, biological, and psychocognitive systems interact with contextual and environmental factors to shape acclimatization and adaptation over the mission span (Lehman et al., 2017). It seems interesting to consider a dynamic biopsychosocial model that views human health in ICE/EUE as the product of reciprocal influences of biological, psychological, cognitive. To these influences should be added the social dynamics that are divided into interpersonal factors and broader contextual dynamics of the mission. All these dynamics unfold over personal and group time. Moreover, the importance, or centrality, of these influences may vary within a person over time. The multilevel in responses to constraints may explained the difficulties to offer a consensual model of acclimatization and adaptation to ICE/EUE. Furthermore, it is necessary to take into account that self-reported psychological measures, cognitive performances and biological outcomes imply different dynamics of responses (Epel et al., 2018). Self-questionnaires use limited Likert-type scaling including interval responses, cognitive performances are based on quantification of errors and/or reaction time for an overview of the cognitive impacts whereas biological outcomes are most often not linear (Epel et al., 2018). Lastly, the use of different variables across multiple studies makes an integrative approach to adaptation in ICE/EUE more difficult. Concerning the main psychological recorded variables, for example, it should be noted that the use of the concepts of emotion and mood is not taken into account. In view of the differences proposed for these affective states, notably in their temporal inscription, it can be suggested that the variations of emotions inform on the adaptation processes and that the variations of mood inform on the adaptation processes.

In order to advance our understanding of how space's and analogs' constraints influences trajectories of health, the recursive and multilevel processes that link ICE/EUE to human responses must be considered in an integrative dynamic approach (Fig. 3). Such an approach conceptualizes health as a system where interpersonal, biological, and psychocognitive systems interact with each other and do so differently in different social contexts. Consequently, a unified roadmap using shared interpersonal, biological, and psychocognitive variables between researchers of this field would be useful. This would allow comparison of data across studies to better understand the processes of acclimatization and adaptation to ICE/EUE and to better consider countermeasures in relation to mission contexts.

Figure 3

A dynamic biopsychosocial model of relevant factors organizing the complexities of acclimatization and adaptation of human to ICE/EUE. Acclimatization refers to a coordinated response to several simultaneous stressors to improve fitness to the environment whereas adaptation explicitly recognizes that stressor-strain relationships unfold over time



4.4. Tomorrow's challenges

Tomorrow's space exploration will impose additional stressors on crews that will be consubstantial to any space life. The latter include the Earth-out-of-view phenomenon, technological aspects (duration/ distance, communication delays), the use of free time, autonomy, and responsibility. Mars is much further from Earth than any other place we have ever been, and this distance significantly changes the mission profile. Although some individuals have been in orbit for more than a year, no human being has spent two years in space with the same crew. Isolation, confinement, monotony, and distance from loved ones is expected to have unprecedented consequences on the health of crew members. Moreover, no individual has ever experienced the Earth-out-of-view phenomenon (Kanas & Manzey, 2008). This phenomenon considers that the fact of no longer seeing and thus feeling the Earth will cause psychic disorders. However, no human being currently experienced it because no one has ventured far enough from Earth. Its consequences can only be imagined and reflexive. Only the first crew on a trip to Mars will be able to answer this question as Earth dwindles in the window. While authors assume that it will result in a profound sense of loneliness (Kanas, 2005; Launius, 2010; Palinkas & Suedfeld, 2021), there is no way to assess the consequences in advance. Kanas (2005) raises the question of a reorganization of the human species in new colonies.

Over time, ICE/EUE living conditions have improved considerably to minimize stressors, and many authors have argued that the community focuses too much on the pathogenic experience of individuals in these extremes (Palinkas, 2003; Shea et al., 2009; Suedfeld, 2005; Vanhove et al., 2014; Zimmer et al., 2013). Due to the nature of ICE/EUE environments, it has been considered for many years that humans cannot adapt. The literature has repeatedly reported the negative effects of exposure to these environments without considering that the lack of result could ultimately be a result. Progressively, salutogenic effects are being describe, but it will take some time to replace the literature focusing only on negative effects and to get a more realistic view of the mechanisms that are really at work. ICE/EUE could also have beneficial and positive consequences (Leach, 2016; Suedfeld, 2001; Suedfeld & Mocellin, 1989; Vakoch, 2012) – some space travelers dream of returning to space, Antarctic winterers go back, and submariners carry out multiple missions. Cherry-Garrard (2013) underlines this ambiguity, noting that an Antarctic expedition is « the worst way to have the best time of your life ». Since the first space missions, space travelers have reported feelings of adventure and accomplishment, pleasure, fulfillment, humility, humanity, and a restructuration of their values (Collins, 1974; Kanas, 1987; Suedfeld & Weiszbeck, 2004). Some compare this to the 'break-off' experienced by fighter pilots, which is a feeling of separation from Earth (Clark & Graybiel, 1957). Similarly, many space travelers have experienced the overview effect. Defined by White (1987), this refers to a profound reaction to viewing Earth from beyond the limits of its atmosphere – an awe-inspiring and self-transcendent experience (Yaden et al., 2016). Several studies report personal growth, increased self-awareness, resilience, self-esteem, self-confidence, and a better ability to cope with stress in the ICE/EUE (Bhargava et al., 2000; Palinkas, 2003; Šolcová & Vinokhodova, 2013; Vakoch, 2012; Zimmer et al., 2013). Palinkas (2003) found that depressed mood was inversely associated with the severity of the physical environment, and that the wintering experience was related to reduced rates of later hospital admissions. This impact of the severity of stressors has also recently been described by Nicolas and collaborators (2021, 2022). Altogether, the literature supports the idea that something happens in these environments that transcends anything these professionals may have experienced before.

Tomorrow's spaceflight will pose challenges that are quite different from those we have already faced. Further work may have practical implications for understanding human behavior in extreme situations (Nicolas et al., 2018), Although the literature reports mixed results on the impact of ICE/EUE on humans, little is known about individual adaptation to such extreme conditions (Fig. 2). If studies on Earth are any indication, future missions involving large crews, more spacious environments, and more sophisticated communications with the outside world should result in fewer psychosomatic complaints, and fewer psychological and cognitive disorders. However, the heterogeneity of existing results means that we cannot draw firm conclusions, and current studies are carried out in environments that do not resemble a trip deeper into the solar system. Finally, targeted countermeasures that help to maintain space travelers' health need to be established (Palinkas & Suedfeld, 2021; Salam, 2020; Stahn & Kühn, 2021). Countermeasures before, during and after space flight are essential. Committee on Space Biology and Medicine (1998b) shed light on countermeasures classified by stages. At the pre-flight stage, learning and training coping strategies is important, especially in males regarding our findings. During in-flight stage, measures include real time monitoring, interventions with the ground and aerospatial medical team, facilitation to specific medical specialties, communication with families. Post flight stage include debriefing, and health evaluation. Manier and Colas (2016) went further by specifying the implementation of a 'psychological seal' before and upon the return from mission.

They also specify the issue of habitats able to meet the challenges of the space environment and mission needs. Currently, countermeasures are being investigated and implemented to overcome spaceflight-associated health risks. The Evidence Based Practice (EBP) perspective is a framework that guides research and intervention practices (Sackett et al., 1996). Originating in medicine, EBP suggests that intervention design rests on three foundational pillars: (1) scientific research knowledge about how interventions work, (2) experiential knowledge of populations and professionals, and (3) consideration of the specific preferences, values, and contexts of target populations (Sackett et al., 1996). Thus, it seems important to conduct studies in line of the EBP perspective. Some papers investigating the potential of noninvasive brain stimulation to modify brain activity (Badran et al., 2020; Romanella et al., 2020). Among them, various techniques are studied including transcranial magnetic simulation, transcranial electric stimulation. These techniques should lead to maintain cognitive performance, increase neuroplasticity, motor system, increase psychological states, decrease psychiatric disorders, and prevent ocular issues during the mission (Romanella et al., 2020). Thus, they are promising tools to maintain health and prevent risks at all levels (i.e., pre-in flight-post) for future long space missions. Botella et al. (2016) explored a psychological strategies program learning to increase positive emotions during mission. However, there are concerns about the assessment of mood and emotions in the literature. Depending on whether one uses the term 'mood' or 'emotions', tools and resources to be developed and applied in individuals may differ. Mood, given its long-term temporal nature, implies practices with beneficial consequences (e.g., diet, physical activity, sleep quality). Emotions arising from a particular event and thus in a sudden and short temporal context suggest a different regulation (e.g., conflict resolution, recontextualization to cope with the situation). These considerations should be taken into account when researchers develop and design countermeasures to improve emotions and mood. Benefits of being mindful have also been investigated to maintain health during a submarine patrol (Aufauvre-Poupon et al., 2021). Also, regular activity and exercise appear beneficial in limiting the effect of isolation and confinement that crew may have (Martin-Krumm et al., 2021; Nicogossian et al., 2016; Petersen et al., 2016; Schneider et al., 2010; Schneider et al., 2013). Furthermore, engagement in these activities is likely to maintain people's perceptions of control over their environment. Nicolas et al. (2021) highlighted the role of perceived control on adaptation processes. Thus, they potentially have feedback effects on the stress level of crews (Gabriel et al., 2020; Lazarus, 1991). Lefranc, submitted) et al. (2021) investigates the association between virtual reality and physical activity to and highlight its benefits to overcome health risks in ICE/EUE environments. Technological advances open the way to new possibilities. The use of virtual reality and digital health are the future of space medicine (Salamon et al., 2018), especially the use of natural virtual scenes (Anderson et al., 2017, Anderson et al., 2018, Anderson et al., 2022). Artificial gravity is under evaluation to prevent the cardiovascular deconditioning as well as ocular alterations during spaceflight (Anderson et al., 2018; Evans et al., 2018; Nicogossian et al., 2016). Bloomberg et al. (2015a) developed a sensorimotor training to increase proprioception and decrease cognitive load of visually dependent subjects. Finally, NASA investigates a lighting countermeasure to synchronize circadian rhythms during Phoenix Mars Lander mission (Barger et al., 2012). This countermeasure has shown its implication to improve sleep and its potential in ISS (Brainard et al., 2016). Also, the research team highlighted the benefits of a blue-enriched light associated with physical activity to improve operationality (Barger et al., 2014; Barger et al., 2021). Nevertheless, countermeasures must be seen as a dynamic structure that can be adjusted to the individual needs identified before the mission, but also in function of the duration and the type of the mission. Thus, countermeasures tailored to each individual and therefore personalized are essentials. This finding underscores that it is fundamental to use an integrative approach with several methodological approaches to better health monitoring and adapt countermeasures. A better understanding of adaptation to ICE/EUE will allow a relevant crew monitoring with a panel of tools sufficiently flexible to be suitable for the crew profiles.

Highlights of this systematic review suggest practical results overview breaking down several disciplines together and proposes some approaches in terms of countermeasures to the main results of this review (Fig. 2).

4.5. Limitations

Our systematic review has several limitations. Firstly, there are few randomized controlled studies (i.e., studies involving a randomly assignation of subjects between an experimental group and a control group). Most of the corpus of articles reports case studies or observational studies, with a medium to low level of evidence, and a risk of bias that is inherent to the environmental conditions. These studies deal with the challenges of conducting studies in extreme environments in which a significant number of constraints must be considered (e.g., high costs, few subjects, permanent adaptability, danger, mission demands). Thus, it is complex to conduct randomized controlled studies under operational and environmental constraints. Nevertheless, they are currently the most reliable means of studying human adaptation to ICE/EUE. Although studies conducted under laboratory conditions are more methodologically reliable, they clearly lack ecological validity. In extreme conditions, cognitive-psycho-physiological factors must be studied with realistic environmental, operational, and time constraints. At the present time, we still cannot say what the impacts of a long trip outside the low Earth orbit will be. Secondly, the reviewed studies are relatively heterogeneous, which is one reason why we could not conduct a meta-analysis. Different methodologies, and the multitude of environments prevent any firm conclusions. In recent years, space agencies have been more willing to collect similar data from research bases in Antarctica. However, the lack of harmonization limits comparisons. Further international collaborations could help to overcome this problem. Third, most reported sample sizes are very small, leading to two issues: a lack of statistical power, and unrepresentative outcomes. Finally, although crews are carefully selected, depending on the country and the environment, the population can be very heterogeneous. Men make up most of the population, and gender differences have not really been taken into account. Implementing selection criteria that reflect those of space travelers would give a better insight and reduce bias. While, overall, these limitations are unavoidable, they contribute greatly to the lack of clarity in the results reported in the literature.

5. Conclusion

Space, characterized by reduced gravity, and environmental and operational stressors, is a hostile environment for the human species. Nevertheless, since the beginning of the space conquest, studies have shown that humans are able to adapt. While NASA’s mission to Mars is expected to last 1100 days, missions to more distant places may be even longer, and will expose crew members to unprecedented risks. Therefore, understanding the impact of the extreme on the individual, and adaptation mechanisms is more necessary than ever to ensure the success of future human space exploration. Analog environments are a valuable way to study the risks. Our results highlight that there has been a slowdown in research since the 1980 s, and there is a need to reconsider how analogs are chosen and used to predict future long-duration space travel. This systematic review covers many disciplinary fields that may not necessarily share the same discourse but are complementary in that they address concepts such as stress, stressors and the framework of adaptation in atypical environments. This integrative approach is the strength of this review. The mixed results reported in the literature underline the fundamental need to harmonize methodologies and report non-changes that could be signs of adaptation. We also need to develop countermeasures to mitigate the harmful effects of ICE/EUE and improve individual performance. We need clear answers to the following questions: Is a human being capable of surviving in such an extreme environment? If so, at what cost? The door to future human space exploration is opening, it is only waiting to take flight.

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7. Supplementary Material

Table 3

Specificities of the environments studied

Title	Author	Year	Type of environment	Infrastructure	Location	Volume	Facilities	Environment characteristics	Length in the environment	Results
520-d Isolation and confinement simulating a flight to Mars reveals heightened immune responses and alterations of leukocyte phenotype	Yi B, Rykova M, Feuerecker M, Jäger B, Ladinig C, Basner M, Hörl M, Matzel S, Kaufmann I, Strewe C, Nichiporuk I, Vassilieva G, Rinas K, Baatout S, Schelling G, Thiel M, Dinges DF, Morukov B, Choukèr A	2014	Spaceflight simulation	Mars 500	N/A	N/A	N/A	N/A	17 months	Increase cortisol levels ; decrease activity ; no signs of elevation in total mood disturbance
A Longitudinal Assessment of Psychological Adaptation During a Winter-over in Antarctica	Décamps G, Rosnet E	2005	Polar station	Durmont d'Urville	Coast of the Dumont d'Urville Sea	N/A	N/A	The real isolation period begins with the departure of the last boat at the beginning of March and lasts approximately for 9 months	12 months	Increase mood disorders ; decrease social reactions ; stabilization of somatic reactions ; no variation of occupational reactions ; no

										association between the third-quarter phenomenon and the occupational reactions ; evidence of a third-quarter phenomenon
Adaptation of heart rate and blood pressure to short and long duration space missions	Verheyden B, Liu J, Beckers F, Aubert AE	2009	Spaceflight	International space station	N/A	N/A	N/A	N/A	6 months	No influence on heart rate and blood pressure
Affective, Social, and Cognitive Outcomes During a 1-Year Wintering in Concordia	Nicolas M, Suedfeld P, Weiss K, Gaudino M	2015	Polar station	Concordia	1 000 km inland from the coast of the Antarctic Ocean (75° 06’ S, 123° 23’ E)	N/A	Two buildings	The station is located at altitude 3 232 m at Dome C. The high Antarctic mainland is one of the coldest (mean temperature of −51°C, the lowest recorded −85°C), driest, most inhospitable and inaccessible regions on the planet. Access to the station is only possible during the Antarctic summer, from mid-November to mid-February. Its atmosphere is	12 months	Variations of stress, mainly in social relations ; association between stress-recovery states, defense mechanisms, symptoms of depression, and lapses of attention-concentration

characterized by chronic hypobaric hypoxia: an altitude equivalent to almost 4 000 m on the equator, with air pressure of about 645 hPa. The crew are totally self-dependent from February to November when no access to or from the is possible, even in emergencies. The living and working quarters are confined to small buildings. Crew is multicultural with different first languages, traditions, and customs. They have limited access and mobility outside the station buildings, especially during winter. They experience long periods of under-stimulation and

								boredom. The strangeness of the environment is increased by the polar nights and days, characterized by continuous light during the Antarctic summer and prevalent darkness during winter		
Alterations in the heart rate and activity rhythms of three orbital astronauts on a space mission	Liu Z, Wan Y, Zhang L, Tian Y, Lv K, Li Y, Wang C, Chen X, Chen S, Guo J	2015	Spaceflight	International space station	N/A	N/A	N/A	N/A	2 weeks	Heart physiology and function changes ; decrease in motion adaptation, decrease in diurnal activity rhythms
Altitude and Seasonality Impact on Sleep in Antarctica	Collet G, Mairesse O, Cortoos A, Tellez HF, Neyt X, Peigneux P, Macdonald-Nethercott E, Ducrot YM, Pattyn N	2015	Polar station	Durmont d'Urville/Concordia	Coast of Antarctica (66°39′ S-140°0′ E); shelf in Antarctica (75°06′ S-123°20′ E); 1 100 km inland from the Durmont d'Urville station	N/A	Several buildings as in a campus/two domes	In Durmont d'Urville, winter is characterized by a brief period of dawn. There are 346 hours of sunshine in December compared to 9 hours in August. Concordia is located 3 233 m above sea level. The base allows for an almost	12 months	Poor sleep efficiency ; no association between location and seasonality

completely confined stay in winter. The atmospheric pressure, due to the latitude, is equivalent to an average altitude of 3 800 m creating environmental conditions of chronic hypobaric hypoxia. During the summer, daylight is constant (mid-November to mid-February). In winter, night is constant for a period of two months with semblance of twilight and dawn during the preceding and following weeks (mid-May to mid-August)

Antarctica challenges the new horizons in predictive, preventive, personalized medicine: preliminary results and attractive hypotheses for multi-disciplinary prospective studies in the Ukrainian « Akademik Vernadsky » station	Moiseyenko YV, Sukhorukov VI, Pyshnov GY, Mankovska IM, Rozova KV, Miroshnychenko OA, Kovalevska OE, Madjar SA, Bubnov RV, Gorbach AO, Danylenko KM, Moiseyenko OI	2016	Polar station	Akademik Vernadsky	Galindez archipelago (65°151, 64°161)	N/A	N/A	The island location is characterized by a limited area, and most of it is covered with the spherical surface of the glacier. The rest of the territory is composed of rocks making it difficult for pedestrian movement and aircraft landing. The thickness of the ozone layer is reduced to 150 Dobson units (i.e., important solar radiation in the ultraviolet range). Temperatures in the winter rarely exceed -30 °C and in summer during a very short period (only during the day) can rise over 0 °C. The average annual temperature in the region of the station is -4 °C. In winter, there are snow drifts	13 months	Increase anxiety, increase stress level ; increase emotional disorders ; adaptation process ; blood pressure, atmospheric pressure drops, and background levels of infrasound changes

								up to 2–3 m.The sun appears for about 35 days during the year. Strong hurricane winds and sudden changes in barometric pressure (40 mmHg or more per day), which are stored for a long time, lead to the fluctuation of oxygen in the ambient air and reduces its partial pressure greater than 10 mmHg		
Antarctica eye study: a prospective study of the effects of overwintering on ocular parameters and visual function	Stahl MH, Kumar A, Lambert R, Stroud M, Macleod D, Bastawrous A, Peto T, Burton MJ	201 8	Trans-Antarctic Winter Traverse	N/A	N/A	N/A	N/A	N/A	8 months	Decrease of retinal thickness, except for the macular and fovea
Assessing Sensorimotor Function Following ISS with Computerized Dynamic Posturography	Wood SJ, Paloski WH, Clark JB	201 5	Spaceflight	International space station	N/A	N/A	N/A	N/A	N/A	Postural impairements

Brain Changes in Response to Long Antarctic Expeditions	Stahn AC, Gunga HC, Kohlberg E, Gallinat J, Dinges DF, Kühn S	2019	Polar station	German Neumayer III	N/A	N/A	N/A	N/A	14 months	Decrease hippocampal volume of dentate gyrus ; decrease gray-matter volume in left parahippocampal gyrus ; decrease right dorsolateral prefrontal cortex ; decrease left orbitofrontal cortex ; BDNF concentration changes ; association between dentate gyrus volume decrease and lower cognitive performance
Cardiovascular Autonomic Adaptation to Long-Term Confinement During a 105-Day Simulated Mars Mission	Wan L, Ogrinz B, Vigo D, Bersenev E, Tuerlinckx F, Van den Bergh O, Aubert AE	2011	Spaceflight simulation	Mars 105	N/A	N/A	N/A	N/A	3 months	Systolic arterial pressure, diastolic arterial pressure, mean arterial pressure changes
Changes in performance and bio-mathematical model performance predictions during 45 days of sleep	Flynn-Evans EE, Kirkley C, Young M, Bathurst N, Gregory K, Vogelpohl V, End A,	2020	Spaceflight simulation	Mars 105	N/A	59 m2	Airlock, hygiene module, crew quarters (e.g., spaceflight simulation workstations, a	The habitat room temperature was maintained at 72 °F (±5 °F), with 70% (±10%) humidity for all missions	1 month	Decrease in cognitive performance ; chronic sleep loss ; association betweenn

restriction in a simulated space mission	Hillenius S, Pecena Y, Marquez JJ						galley, a communication station, an aerobic exercise station, and private sleep quarters)			chronic sleep loss and performance impairment ; subjective fatigue unchanged
Changes in sleep patterns during prolonged stays in Antarctica	Bhattacharyya M, Pal MS, Sharma YK, Majumdar D	2008	Polar station	Maitri	1 800 km from the South Pole, Schimarcher Oasis (70° 45′ 39″ S, 11° 44′ 49″ E)	N/A	N/A	The station is located at an altitude of 120 m. The sun is continuously seen above the horizon from November to February and remains below the horizon from May to August. The main station was centrally heated, with the temperature maintained between 22 and 25°C irrespective of the outside temperature. The highest maximum and minimum ambient temperatures recorded around Maitri were 6°C in January and −37°C in July	12 months	Decrease in total sleep time ; increase in duration of waking period after sleep, and sleep latency ; decrease in slow wave sleep ; increase in first stages of sleep ; increase rapid eye movement sleep ; association between sleep parameters and time

Circadian Levels of Serum Melatonin and Cortisol in relation to Changes in Mood, Sleep, and Neurocognitive Performance, Spanning a Year of Residence in Antarctica	Premkumar M, Sable T, Dhanwal D, Dewan R	2013	Polar station	Maitri	70°45’S, 11°44’E	N/A	N/A	The winter period at 70 S starts in mid April and lasts till October	13 months	No cortisol level changes ; decrease circadian secretion of melatonin ; association between melatonin levels, better sleep quality, lower depression scores, and better performance ; evidence of the winter-over syndrome
Circadian Rhythm and Sleep During Prolonged Antarctic Residence at Chinese Zhongshan Station	Chen N, Wu Q, Xiong Y, Chen G, Song D, Xu C	2016	Polar station	Zhongshan Station	Larsemann Hills of Princess Elizabeth Land, East Antarctic (69122024″ S, 76122040″ E)	N/A	N/A	The lowest air temperature in 2011 was 30.11°C. The continuous day is 62 days, and the continuous night is 58 days. The researchers live for 2 months of the winter with exclusively artificial light (200 lux) but can expose themselves to daylight during the summer. The light-dark cycle is the	15 months	Delayed circadian rhythm desynchronization ; delayed sleep phase ; later chronotype) ; increase depression, increased appetite, increase fatigue, decrease sociability ; evidence of subsyndromal seasonal

								predominant zeitgeber for synchronizing or driving the human circadian rhythm over the 24-hour day. Lightdark cycle is the predominant zeitgeber for synchronizing or entraining human circadian rhythm to the 24-hour day		affective disorder
Circadian Rhythm of Autonomic Cardiovascular Control During Mars500 Simulated Mission t	Vigo DE, Tuerlinckx F, Ogrinz B, Wan L, Simonelli G, Bersenev E, Van Den Bergh O, Aubert AE	201 3	Spacefligh t simulation	Mars 500	N/A	550 m3	Four hermetically sealed interconnected habitat modules: medical module (two medical berths, medical and research equipment, toilet), habitable module (six compartments, main control room, toilet), storage module (physical training facilities, food storage,	Communication with Mission Control on a 24/7 basis. Ambient temperature maintained constant at 24°C, with a relative humidity of 35–45%, and artificial lighting conditions of 50–300 lux	17 months	Decrease amplitude of the rest-activity pattern of autonomic nervous system parasympatheti c function ; increase mean RR interval ; increase amplitude of very low and high frequencies ; decrease high frequency during sleep ; nonsignificant circadian rhythms towards HRV

							greenhouse, bathroom), Mars landing module simulator, and one external module, simulating the Martian surface			
Cognitive demand of human sensorimotor performance during an extended space mission: a dual-task study	Bock O, Weigelt C, Bloomberg JJ	2010	Spaceflight	International space station	N/A	N/A	N/A	N/A	6 months	Decrease in visuomotor performance
Cognitive Performance During Confinement and Sleep Restriction in NASA's Human Exploration Research Analog (HERA)	Nasrini J, Hermosillo E, Dinges DF, Moore TM, Gur RC, Basner M	2020	Spaceflight simulation	HERA	NASA's Johnson Space Center (USA)	148.6 m3	2 cylindrics divided into four sections: the core (56.0 m3), loft (69.9 m3), airlock (8.6 m3), and hygiene module (14.1 m3)	Mission control monitored activities in the facility 24/7. They could see and hear via audiovisual feeds what was going on in the facility at all times except during periods where communication time delays were simulated. Communication of researchers with the crew was relayed through mission control.	2 weeks	Decrease in cognitive performance ; increase in affects

Communication to the outside world is restricted through a simulated mission control center, with a weekly scheduled family conference, which simulates the relative isolation of typical spaceflight missions. The physical features of the HERA habitat itself mimic the confinement of a spacecraft environment. Other logistic features of the missions like type and duration of activities, diet, access to exercise, and the introduction of sleep challenges and stressful tasks are all designed to replicate the operational challenges of spaceflight

Cognitive performance during long-term residence in a polar environment	John Paul FU, Mandal MK, Ramachandran K, Panwar MR	2010	Polar station	Maitri	70°45′S, 11°44′E	N/A	N/A	N/A	14 months	Increase recognition memory ; increase learning learning ; short-term memory performance stable
Confinement has no effect on visual space perception: The results of the Mars-500 experiment	Sikl R, Simeček M	2013	Spaceflight simulation	Mars 500	N/A	N/A	N/A	N/A	17 months	Alterations in perception in 2D ; no changes for 3D perception
Coping with Antarctic demands: Psychological implications of isolation and confinement	Tortello C, Folgueira A, Nicolas M, Cuiuli JM, Cairoli G, Crippa V, Barbarito M, Abulafia C, Golombek DA, Vigo DE, Plano SA	2020	Polar station	Belgrano II	1 300 km away from the South Pole, Nunatak Bertrab (77° 51′S, 34° 33′W)	N/A	N/A	The station is one of the most isolated, driest and coldest territories in the world. Temperatures ranging from −43°C during winter to 5°C during summer. It has 4 months of constant light (polar day) and 4 months of constant darkness (polar night). Every year a crew of 15–20 men spend 1 year living	13 months	Decrease coping strategies ; association between social support and recovery from stress

Cortical reorganization in an astronaut's brain after long-duration spaceflight	Demertzi A, Van Ombergen A, Tomilovskaya E et al	2016	Spaceflight	International space station	N/A	N/A	N/A	N/A	6 months	Alteration in vestibular and motor-related regions ; association between the precentral as well as postcentral gyrus and cerebellum and voluntary motor initiation, proprioception, motor coordination
Different adaptations of Chinese winter-over expeditioners during prolonged Antarctic and sub-Antarctic residence	Chen N, Wu Q, Li H, Zhang T, Xu C	2016	Polar station	Great Wall Station/Zhongshan Station	King George Island, northwest of the Antarctic Peninsula (62° 12′ 59″ S, 58° 57′ 52″ W); Larsemann Hills of Princess Elizabeth Land, East Antarctica (69° 22′ 24″ S, 76° 22′ 40″ E)	N/A	N/A	The Great Wall station does not experience polar day (i.e., 24 h daylight) or polar night (0 h daylight). The average number of daylight ranges from 5 h in June to 19.5 h in December. Zhongshan Station has polar days lasting for 54 days and polar nights for 58 days. Indoor living compartment temperature at both stations was	12 months	Mood patterns changes ; association between negative mood and the severity of environment : no systolic and diastolic blood pressure changes

								between 15 and 20 °C		
During the Long Way to Mars: Effects of 520 Days of Confinement (Mars500) on the Assessment of Affective Stimuli and Stage Alteration in Mood and Plasma Hormone Levels	Wang Y, Jing X, Lv K, Wu B, Bai Y, Luo Y, Chen S, Li Y	201 4	Spacefligh t simulation	Mars 500	Institute for Biomedical Problems of Moscow (Russia)	N/A	N/A	The spaceship-like habitat with continuous temporal and spatial isolation, realistic mission activities, a diurnal weekly work schedule, communication lag, a mid-mission landing on a simulated Mars surface and other major special conditions of a Martian flight	17 months	Assignation to positive ratings to negative pictures ; association between psychological and biochemical data
Dynamics of stress and recovery and relationships with perceived environmental mastery in extreme environments	Nicolas M, Martinent G, Suedfeld P	202 2	Polar station	Kerguelan station & Durmont d'Urville	48°27'-50°00'S, 60°27'-70°35'E (Kerguelen station); 66°40'S – 140°01'E (Dumont d'Urville)	7 215 km2 (Kerguelen station)	N/A	Kerguelen station is located in the extreme south of the Indian Ocean, include on average 300 islands, hosts a crew of 50 in winter and 100 in summer, have on	12 months	Increase of stress response and decrease of recovery dependant of the caracteristics of the environment, environmental

								average 4.9°C, frequent precipitation including snow, continious wind between 35 to 150 km/h, high humidity, complexe access. Dumont d'Urville is located in Adelie Island on the Southern Ocean coast of the Antarctic land, hosts of a crew of 30 in winters and 100 in summer, temperatures from -40°C to 0°C (on average -1°C in summer and -18°C in winter), extreme winds between 140 to 210 km/h, unusual light-dark cycles from February to November, no access during winter		mastery impact stress responses dynamics
Effects of Long-Term Isolation and Anticipation of Significant Event on Sleep: Results of the	Zavalko IM, Rasskazova EI, Gordeev SA, Palatov SU,Kovrov GV	201 3	Spacefligh t simulation	Mars 500	N/A	N/A	N/A	The crew was isolated in the spaceship model. They were only in communication	17 months	Prolongation of sleep latency ; decrease sleep efficiency ; increase frequency of

Project «Mars 520 »								with the outside through a local area network (no TV or internet). Natural light was not present. Astronauts had a very busy schedule with some free time for hobbies		the nights with low sleep efficiency ; anticipation highlighted as a factor in sleep modification
Environmental influences on hypothalamic-pituitary-thyroid function and behavior in Antarctica	Palinkas LA, Reedy KR, Shepanek M, Smith M, Anghel M, Steel GD, Reeves D, Case HS, Do NV, Reed HL	2007	Polar station	McMurdo & South Pole stations	Latitude 78.48 S, altitude 12m (McMurdo) ; latitude 90 S, altitude 3880m (South Pole stations)	N/A	N/A	N/A	2 to 12 months	Polar T3 Syndrome; increase of physiological responses to cold and altitude at South Pole stations
Exposure to an extreme environment comes at a sensorimotor cost	Kim KJ, Gimmon Y, Sorathia S, Beaton KH, Schubert MC	2018	Aquarius habitat	NEEMO	19m undersea, 5.6 km off the coast of Key Largo in the Florida Keys National Marine Sanctuary (USA)	N/A	Undersea station	There is a saturated atmospheric pressure (~2.5 atm.), a limited space to move, and a persistent threat of danger	2 weeks	Decrease in sensorimotor performance

Extreme Environment Effects on Cognitive Functions: A Longitudinal Study in High Altitude in Antarctica	Barkaszi I, Takács E, Czigler I, Balázs L	2016	Polar station	Concordia	Antarctic Plateau	N/A	N/A	The station is located on the Antarctic Plateau 3 233 m above sea level. It is one of the coldest places on Earth, in 2011 the average air temperature was −51.2◦ C (min. −76.4◦ C, max. −19◦ C). The air temperature of that year was −35.8◦ C in summer and −64.4◦ C in winter. The sun disappears completely during winter (from 2–3 of May to 9–10 of August). People experience hypoxia, fluctuation of sunshine duration, isolation and confinement. The average air pressure was 482.5 Hgmm between February and December 2011. The average	12 months	No negative impacts on cognitive activity during the winter

								nocturnal oxygen saturation was 85.1–87.9% during the campaign		
Hormonal, autonomic cardiac and mood states changes during an Antarctic expedition: From ship travel to camping in Snow Island	Moraes MM, Bruzzi RS, Martins YAT, Mendes TT, Maluf CB, Ladeira RVP, Núñez-Espinosa C, Soares DD, Wanner SP, Arantes RME	2020	Polar station & ship travel	Snow Island	South Shetland Islands (62°43′51.8″ S, 61°12′33.1′′ W)	N/A	N/A	Exposure to cold environment between 9:00–10:00 am and 5:00–6:00 pm. The ambient temperature of the camping region was, on average, 2 °C (range: from −2 °C to 7 °C). The average ambient temperature values was 4.4 ± 1.2 °C (from 1.0 °C to 7.9 °C). During the camping days (i.e., between January and February), the daylight period lasted from 17 h 31 min to 15 h 19 min, with periods of astronomical twilight (January: 0 h; February: 4 h 35 min), nautical twilight (January: 4 h 2	2 months	Cardiac autonomic regulation changes ; increase in depression ; cortisol level modifications, increase oscillations in tension and confusion

								min; February: 2 h 31 min) and civil twilight (January: 2 h 27 min; February: 1 h 45 min)		
How stressful are 105 days of isolation? Sleep EEG patterns and tonic cortisol in healthy volunteers simulating manned flight to Mars	Gemignani A, Piarulli A, Menicucci D, Laurino M, Rota G, Mastorci F, Gushin V, Shevchenko O, Garbella E, Pingitore A, Sebastiani L, Bergamasco M, L'Abbate A, Allegrini P, Bedini R	201 4	Spacefligh t simulation	Mars 105	N/A	N/A	N/A	The isolation facility was artificially lighted (16 hours on, 8 hours off), ambient temperature was maintained constant at 24 °C, and an environmental noise in line with that of the ISS (60-70 dB) was constantly present. Once sealed into the facility, the crewmembers had only personal contact with each other and a time-limited voice contact with a simulated control centre was the only connection with the outside. Inside the isolation facility, daily tasks were organised in	3 months	Sleep structure modifications ; increase sleep pathologies ; associations between cortisol and sleep changes ; no cognitive decline ; no decrease in emotional state

							order to match those typical of human spaceflight missions		
Human change and adaptation in Antarctica: Psychological research on Antarctic wintering-over at Syowa station	Kuwabara T, Naruiwa N, Kawabe T, Kato N, Sasaki A, Ikeda A, Otani S, Imura S, Watanabe K, Ohno G	2021	Polar station	Syowa Station	Small island 4 km from the continent (S 69°, E 39°)	N/A	N/A	The temperature is 0°C in summer, minus 40°C in winter. There is uninterrupted sunlight in December and January and polar nights without any sunrise in June and July	12 months	Fewer physical health risks in Antarctica than in Japan ; coping mechanisms; no emotional disorders ; positive affect stable
Human factors research as part of a Mars exploration analogue mission on Devon Island	Binsted K, Kobrick RL, Griofa MÓ, Bishop S, Lapierre J	2010	Polar station	Flashline Mars Arctic Research Station	Devon Island (Canada)	N/A	Small crew quarters	Simulated constraints of a Mars surface exploration mission. Life is rare on the island with temperatures reaching as low as -40° at the start of the summer season. The layout of the habitat offers some visual privacy but the walls are not soundproof. Crewmembers could only exit the habitat in a	4 months	Increase psychological disorders ; cognitive modifcations without decrements was highlighted. More active coping strategies in woman than man

								simulated spacesuit as part of an organized traverse, after having spent 5 min in the airlock all communications with the outside world were subject to a 20 min delay, food was shelf-stable without refrigeration, water use was tightly restricted and monitored		
Investigating human cognitive performance during spaceflight	Pattyn N, Migeotte PF, Demaeseleer W, Kolinsky R, Morais J, Zizi M	2005	Spaceflight	International space station	N/A	N/A	N/A	N/A	6 months	Alteration of cognitive functions
Locus of Control, Stress Resistance, and Personal Growth of Participants in the Mars-500 Experiment	Solcova I, Vinokhodova AG	2015	Spaceflight simulation	Mars 500	Institute for Biomedical Problems of Moscow (Russia)	N/A	N/A	Simulate all major elements of an interplanetary flight to Mars: a flight to Mars, orbital flight around Mars with subsequent landing, and return to the Earth. Living conditions (communication, food supply,	6 months	Resilient coping ; emotional stability

								humidity, temperature, pressure, and gas composition) corresponded to those of the ISS. Daily timeline was analog to this employed on ISS: the crew performed maintenance, experiments, and other activities in the analog manner		
Long-duration spaceflight adversely affects post-landing operator proficiency.	Moore ST, Dilda V, Morris TR, Yungher DA, MacDougall HG, Wood SJ	201 9	Spacefligh t	International space station	N/A	N/A	N/A	N/A	6 months	Decrease in manual dexterity, dual-tasking and motion perception, and in striking degradation to operate a vehicle
Mars 520-d mission simulation reveals protracted crew hypokinesis and alterations of sleep duration and timing	Basner M, Dinges DF, Mollicone D, Ecker A, Jones CW, Hyder EC, Di Antonio A, Savelev I, Kan K, Goel N, Morukov BV, Sutton JP	201 3	Spacefligh t simulation	Mars 500	N/A	N/A	N/A	The facility included a spaceship-like habitat, continuous isolation from Earth's environment, realistic mission activities, midmission landing on a simulated Mars	17 months	Sleep disorders ; association between performance impairment, sleep deprivation and subjective sleep quality

									surface, accurate mission duration and timeline, operations between crew and mission controllers, communication delays, limited consumable resources, exercise equipment for physical fitness, diurnal weekly work schedule, crew control of habitat lighting, and video monitoring of crew in habitat common areas		
Mars-105 study: Time-courses and relationships between coping, defense mechanisms, emotions and depression	Nicolas M, Sandal G, Weiss K, Yusupova A	201 3	Spacefligh t simulation	Mars 105		Institute for Biomedical Problems of Moscow (Russia)	550 m3	Four hermetically sealed interconnected habitat modules: principal living quarters (kitchen-dining room, iving room, main control room, toilet, six individual rooms with a bed, a desk, a personal	Modules under conditions of artificial atmospheric environment at normal barometric pressure	3 months	Decrease in psychological states

							computer, a chair and shelves for personal belongings), medical (routine medical and telemedical examinations, laboratory, diagnostic investigations and isolation), storage (food storage room, experimental greenhouse, bathroom, sauna, gym), and one external module used to simulate the 'Martian surface'			
Mental and Physical Workload, Salivary Stress Biomarkers and Taste Perception: Mars Desert Research Station Expedition	Rai B, Kaur J	2016	Spaceflight simulation	Mars desert	American southwest desert region (USA)	N/A	Similar to Mars Reference Mission guidelines	Crew members must wear an analogue space suit simulator or a sim suit when completing tasks outside the Habitat to simulate the protection they would need from the harsh Martian environment	2 weeks	Decrease in taste sense

Modulations of Neuroendocrine Stress Responses During Confinement in Antarctica and the Role of Hypobaric Hypoxia	Strewe C, Thieme D, Dangoisse C, Fiedel B, van den Berg F, Bauer H, Salam AP, Gössmann-Lang P, Campolongo P, Moser D, Quintens R, Moreels M, Baatout S, Kohlberg E, Schelling G, Choukèr A, Feuerecker M	2018	Polar station	Concordia/Neumayer III	High ice plateau area or Dome C (75◦ 06′ S/123◦ 21′ E); Atka Bay in the northeast Weddell sea on the Ekström shelf ice (70◦ 40′ S/8◦ 16′ W)	N/A	N/A	Concordia is located situated at 3 233 m above sea-level in high altitude. The pressure level is approximately 640 to 650 hPa. The closest coastal region is approximately 1 100 km away. Neumayer III station is at sea level. Seasons in Antarctica are opposite to the northern hemisphere with Antarctic summer lasting from beginning of November to beginning of February and winter from May to August. The longest day (mid-summer) is in December and the shortest day in June (mid-winter). During the Antarctic summer the lack of a light/dark cycle results in 24 h of constant sunlight. During	11 months	Distinct modulating effect on stress response ; no association with psychological stress

this period, average outside temperatures are around −50◦C (Concordia, high altitude) and −3◦C (Neumayer III, sea level). By contrast, during the winter season no sunlight is present and outside temperatures range around −60◦C and can drop to −80◦ C at Concordia (high altitude) and −30◦ C at Neumayer III (sea level). In addition to the extreme outside temperatures, humidity is very low especially in inner Antarctica (Concordia, high altitude) leading to a very dry environment. Precipitation is very little throughout the year. Telecommunication with the outside world

								from the stations is possible via phone. The same applies for internet access that is possible but not always reliable		
Multi-System Adaptation to Confinement During the 180-Day Controlled Ecological Life Support System (CELSS) Experiment	Yuan M, Custaud MA, Xu Z, Wang J, Yuan M, Tafforin C, Treffel L, Arbeille P, Nicolas M, Gharib C, Gauquelin-Koch G, Arnaud L, Lloret JC, Li Y, Navasiolava N	2019	Spaceflight simulation	CELSS	N/A	370 m2 (888.5 m3 of greenhouses)	Six interconnected modules and eight compartments including two crew cabins (individual bedrooms, working area, medical monitoring area, cafeteria, and gym), four greenhouses, resource cabin, and life support cabin	The resource cabin recycle and prurify systems to deal with waste (feces, urine, plant debris, waste water, exhaust gas) and produce CO2 for plants. Life support systems were controlled automatically. Crew members had to autonomously meet their vital needs of air, water, and foodin the station. To imitate Mars conditions during the experiment, the crew lived for 36 days on Martian day–	6 months	No additional stress ; no impaired physiological and psychological states

night cycle of 24 h and 40 min with realistic interruption of communication with Earth. Based on considerations for energy and dietary requirements, as well as multiple taste preferences and health issues, crewmembers cultivated 25 kinds of plants including wheat, potatoes, sweet potatoes, soybeans, peanuts, lettuce, cabbage, edible amaranth, cherry radish, tomatoes and strawberries. Social psychological support included phone and video calls with family and friends every 15 days for 30 min. Otherwise, phone could only be used to discuss the work in cabin with Control room.

								Crew was not allowed to communicate with outer world via internet. Also, CELSS modules were kept under artificial lighting conditions. Crewmembers lived on Mars time from day 72 to day 108, with a day–night cycle of 24 h and 40 min. The Martian period lasted for 36 « Martian » days, which was equal to 37 « Terrestrial » days (53280 min). Otherwise, volunteers lived on Earth time with a 24-h day–night cycle set to 16 h:8 h (16 h 27 min:8 h 13 min for the Martian period)		
Neurophysiological, neuropsychological, and cognitive effects of 30 days of isolation	Weber J, Javelle F, Klein T, Foitschik T, Crucian B, Schneider S, Abeln V	2019	Spaceflight simulation	HERA	N/A	N/A	N/A	N/A	1 month	Increase in cortisol level ; no changes on cortical activity, cognition, and mood

Neurovestibular Symptoms in Astronauts Immediately after Space Shuttle and International Space Station Missions	Reschke MF, Good EF, Clément GR	2017	Spaceflight	International space station	N/A	N/A	N/A	N/A	6 months	Walking and postural instabilities ; exaggerated perceived motion associated with sudden head movements
Physiological phenotypes and urinary metabolites associated with the T psychological changes of healthy human: A study in ‘‘lunar palace 365”	Hao Z, Fenga S, Zhua Y, Yanga J, Menga C, Hua D, Liua H, Liua H	2020	Spaceflight simulation	Lunar Palace	N/A	160 m2 (500 m3)	One comprehensive cabin (four private bedrooms, living room, bathroom, and insect culturing room), and two plant cabins	Each bedroom is very small, only containing a single bed and a small table. In order to simulate the space mission delay due to the launch window, climatic conditions or other unexpected situations, on the 340th day of isolation, the isolated time was suddenly extended by five days. The crewmembers had no visual contact to outside scenery (window covered with opaque papers). Accidental powered failures occured several times	2 to 7 months	Decrease negative mood scores ; increase positive mood scores ; association between cardiovascular changes and psychological states

Preparing for Mars: human sleep and performance during a 13 month stay in Antarctica	Mairesse O, MacDonald-Nethercott E, Neu D, Tellez HF, Dessy E, Neyt X, Meeusen R, Pattyn N	2018	Polar station	Concordia	Antarctic plateau Dome C (75°6 0 S, 123°20 0 E)	N/A	N/A	The station is located at an altitude of 3 233 m (equivalent to 3 800 m corrected for atmospheric pressure). The station sits in the largest desert in the world. Average atmospheric pressure is around 645 hPa with 36% lower oxygen levels than at sea level. Relative air humidity is often as low as 0.03%. Temperatures hardly rise above −25°C in summer and can fall below −80°C in winter. The base allows for a confined stay during the winter, with few crew members going outside and only for short duration technical or scientific duties. Communications with outside	13 months	Increase sleep onset latencies ; reduced psychomotor speed

								operators is limited to short text messages via satellite, approximately once every 8 hours. Day–night cycles at the station are imposed by daily routines rather than daylight, which is entirely absent for about 3 months during the polar winter		
Prolonged Microgravity Affects Human Brain Structure and Function.	Roberts DR, Asemani D, Nietert PJ, Eckert MA, Inglesby DC, Bloomberg JJ, George MS, Brown TR	2019	Spaceflight	International space station	N/A	N/A	N/A	N/A	1 to 6 months	Increase in ventricular volume for the left lateral, right lateral, third, and fourth ventricles associated with length of the mission, but negatively with age ; cognitive and motor test scores changes and correlated with specific brain structures

Psychological adaptation of Indian expeditioners during prolonged residence in Antarctica	Khandelwal SK, Bhatia A, Mishra AK	2017	Polar station	Maitri	100 km inland from the Princess Astrid coast of East Antarctica, Schirmacher Oasis (70°45’S, 11°44’E)	N/A	N/A	The station is located at an altitude of 100 m above sea level. Temperatures range from roughly +5°C in summer to −35°C in winter. Average annual temperature is −11°C. Wind speeds regularly touch 100 km/h, with an increased frequency during the winter season. High-speed winds frequently cause blizzards. The nearest station is Novolazarevskaya located 10 km away. The station is accessible by air and sea only during the limited summer season lasting from November to February. The station is physically cutoff during the remaining 8 months. Polar day (period of 24 h sunlight) and	12 months	Increase anxiety ; increase insomnia during the coldest period ; depressive symptoms unchanged ; decrease cognitive performance ; no evidence of the third quarter phenomenon ; psychological adaptation

								polar night (period of 24 h absence of sunlight) last for 2 months each, from November to January and May to July, respectively. The station can support 25 personnel during the winter and roughly 40 during summer		
Psychological and Behavioral Changes during Confinement in a 520-Day Simulated Interplanetary Mission to Mars	Basner M, Dinges DF, Mollicone DJ, Savelev I, Ecker AJ, Di Antonio A, Jones CW, Hyder EC, Kan K, Morukov BV, Sutton JP	201 4	Spacefligh t simulation	Mars 500	N/A	550 m3	Interconnected habitable modules	Pressurized facility with a volume and configuration comparable to a spacecraft. Facility modules are equipped with life support systems and an artificial atmospheric environment at normal barometric pressure. Activities simulated the ISS daily work, scientific experiments, and exercise, isolation from Earth's daily	17 months	Behavioral (e.g., changes in sleep-wake behavior) and psychological (e.g., emotional states, sleep troubles, depression) changes

environmental light-dark cycles, temperatures and seasonal conditions. There was a Mars flight simulation based in orbital mechanics and under the direction of mission controllers, with a 30-day Mars orbiting phase (between mission days 244 and 273). 3 of the 6 crewmembers simulating egresses on the Martian surface (between mission days 257 and 265). Work throughout the mission included both routine and simulated emergency events, changes in communication modes and time delays between mission days 54 and 470, limited consumable resources (food

								and water), and media publicity		
Psychological Hibernation in Antarctica	Sandal GM, van deVijver FJR, Smith N	2018	Polar station	Concordia	1 000 km inland from the coast of the Antarctic Ocean (75° 06′ S, 123° 23′ E)	1 500 m2	Three towers connected by enclosed walkways. The first one, called the quiet building, contains individual sleeping quarters, two bathroom, three toilets, hospital, laboratories (glaciology, meteorology, astronomy). The second tower, dedicated to noisy rooms, houses the canteen, workshop, the waste water treatment plant, social rooms (for	The French-Italian research station has the driest desert climate on Earth, a low air-pressure and an oxygen-poor atmosphere. The mean temperature is −51°C, the lowest recorded temperature is −8°C. Access to the station is only possible from November to February due to the cold and darkness. The temperature inside the base is usually between 21 and 23°C. The base can accommodate about 60 people during the short	10 months	Low negative feelings ; positive states and coping strategies changes ; associations between psychological variables and time ; hibernation as a new coping mechanism

							video-watching, music), gym, kitchen, and storage rooms. The third tower is made up of eleven container size modules where the electric power plant, the boiler room and a second workshop	summer period, and can hold 15-16 crew members during winter. Time spent outside the base during winter is minimal because of the extreme temperatures which again may lead to under-stimulation and boredom due to the monotony of the indoor facilities. Communications with the outside world were limited to satellite telephone, restricted email contacts and there was no internet access at the time of the data collection		
Reductions in circulating endocannabinoid 2-arachidonoylglycerol levels in healthy human subjects exposed to chronic stressors	Yi B, Nichiporuk I, Nicolas M, Schneider S, Feuerecker M, Vassilieva G, Thieme D, Schelling G, Choukèr A	2016	Spaceflight simulation	Mars 500	N/A	N/A	N/A	N/A	17 months	Psychology (e.g., positive emotions) and physiology (e.g., decreased brain cortical activities) changes ; no negative

										emotions modifications
Shifts in broadband power and alpha peak frequency observed during long-term isolation	Weber J, Klein T, Abeln V	2020	Spaceflight simulation	SIRIUS	N/A	N/A	Medical and laboratory compartment, and separated compartments (physical training, kitchen, living room, private dorms, storage, lavatories and technical operations)	Simulate a journey to the Moon with extravehicular activities on the lunar surface and back to Earth	4 months	Increase cortical deactivation
Sleep during an Antarctic summer expedition: new light on « polar insomnia »	Pattyn N, Mairesse O, Cortoos A, Marcoen N, Neyt X, Meeusen R	2017	Polar station	Belgian station	Princess Elisabeth (l71°57′ S; 23°20′ E)	N/A	N/A	Altitude 1 382 m, corrected equivalent of 1 800 m	4 months	Increase polar insomnia ; decrease slow-wave sleep and ultradian sleep structure distortion. No significant effect on mood
Sleep patterns of crewmembers in mission IV of the Hawaii space exploration analog and simulation (HI-SEAS): a pilot study	Matsangas P, Lewis Shattuck N, Heinicke C, Dunn J	2017	Spaceflight simulation	HI-SEAS	Solar-powered geodesic dome in the Mauna Loa volcano (Hawaï)	368 m3	The habitat is divided into two levels: common areas (i.e., kitchen, lab, work area, and bathroom) located on the first level with approximately 84 m2;	Crews are isolated during their missions with only e-mail communication (i.e., 20-minute delay with the outside world). Station is located at 8,200 feet above sea level.	12 months	Sleep-related behaviors, physical activity and exposure to light modifications

						staterooms and a half-bath are located on the 39 m2 upper level; and an attached workshop	The dome is compised of an aluminum frame with a white vinyl covering (i.e., reddish camouflage most of the time). Crewmembers have a limited water supply and can shower only for a total of 6-8 minutes per week. When outside the habitat for extravehicular activities, the crewmembers wear mock space suits		
Sleep Quality Changes during Overwintering at the German Antarctic Stations Neumayer II and III: The Gender Factor	Steinach M, Kohlberg E, Maggioni MA, Mendt S, Opatz O, Stahn A, Gunga HC	201 6	Polar station	Neumayer II/Neumayer III	Atkabay on the Ekström-shelf ice (70°40'S, 8°16'W)	Underground with two tube constructions connected to each other composed of air-conditioned (e.g., laboratories, workshops, sickbay, sauna, dining room, conference room, medical treatment rooms). In a last tube: chill	Stations are isolated (i.e., inaccessibility, small crew size). Adverse weather conditions during the darkness-phase made it nearly impossible to reach the station by airplane or ships. Communication with the outside is made with Internet and different satellite	13 months	Sleep patterns changes ; gender influence with decrease in sleep quality for woman, despite an unchaiged physical activity

camps, garbage storage, vehicle garage	communication systems. Emergency rescues would have been practically impossible. Since February 2009, the new Neumayer Station III is in operation. Due to the risks involved (e.g., fall, frostbite and hypothermia), the outside-activity during the Antarctic winter was reduced to a minimum. People was equipped with cold-protection clothing and emergency equipment when needed. For a period of about 60 days around midwinter (21st of June), virtually no sunlight reached locations at that latitude, while for another 20 days before and after that period

the sunshine radiation was very low, which led to periods of complete darkness between the end of May and the end of July. Less than 50 W/m2 of sunshine radiation were measured between beginning of April until the end of September, and less than 5 W/m2 from the mid of May until the beginning of August, respectively. Sunshine duration was less than about 5 hours per day from mid-April to end of August and virtually zero from mid-May to the beginning of August. Sunshine from November to January during the Antarctic summer. Temperatures

								varies between 2008 to 2011 around –2.7 ± 2.0°C (n = 124) and – 25.2 ± 7.2°C (n = 124) in January and July		
Sleep Stability and Cognitive Function in an Arctic Martian Analogue	Gríofa MO, Blue RS, Cohen KD, O'Keeffe DT	2011	Polar station	Flashline Mars Arctic Research Station	Devon Island (Canada)	N/A	N/A	Station is used to conduct long-duration analogue studies designed to mimic conditions of a future mission to the Martian or lunar surface. It is the largest uninhabited island on Earth and visible life is rare. Temperatures reaching as low as -40°C. Privacy is limited in crew quarters and walls are not soundproof. While the habitat itself provides artificial	1 month	Increase in subjective sleep and alertness ; no alteration of sleep patterns ; no cognitive decline

								temperature and lighting, the surrounding environment is exposed to 24 h of direct sunlight		
Sleep-wake differences in heart rate variability during a 105-day simulated mission to Mars	Vigo DE, Ogrinz B, Wan L, Bersenev E, Tuerlinckx F, Van Den Bergh O, Aubert AE	2012	Spaceflight simulation	Mars 105	N/A	N/A	Four connected habitat modules (medical module, habitable module, storage module, and Mars landing module) and one external module, simulating the Martian surface	N/A	3 months	Decrease HRV and heart rate ; increase frequency amplitude ; decrease sleep-wake high frequency ; sleep HRV stable
Sleep, napping and alertness during an overwintering mission at Belgrano II Argentine Antarctic station	Folgueira A, Simonelli G, Plano S, Tortello C, Cuiuli JM, Blanchard A, Patagua A, Brager AJ, Capaldi VF, Aubert AE, Barbarito M, Golombek DA, Vigo DE	2019	Polar station	Belgrano II	1 300 km from the South Pole (77° 51′S and 34° 33′W)	N/A	N/A	The station is one of the southernmost permanent stations on the planet. It has around four months (from October 22nd to February 18th) of day, four months (from February 19th to April 23rd and from August 19th to October 21st) of	12 months	Decrease sleep duration ; effect of seasonality in the association of evening alertness with sleep onset ; no blood pressure changes

variable day lengths and four months (from April 24th to August 18th) of night. The temperature ranges between 5°C in summer and −43°C in winter, with gusts of wind above 200 km/h. To generate a light-dark cycle during the summer, windows with closed blinds are used during the « night ». Exposure to ultraviolet light is also stronger and the personnel of the stations require solar glasses for external work. During the winter, the light-dark cycle relies entirely on artificial lighting. The estimated illuminance was 170 lx to 330 lx in bedrooms, 290 lx in common

								areas and 510 lx in the medical room		
Sleeping under the Ocean: Despite Total Isolation, Nuclear Submariners Maintain Their Sleep and Wake Patterns throughout Their Under Sea Mission	Trousselard M, Leger D, van Beers P, Coste O, Vicard A, Pontis J, Crosnier SN, Chennaoui M	2015	Submarine	« Téméraire » French Strategic Submarine with Ballistic Nuclear missiles	N/A	N/A	N/A	Temperature was maintained between 18 and 25°C, light was scheduled to reproduce a 24-hour daylight/nighttime cycle, with 16 hours of daytime levels (90 to 840 lux) and 8 hours (from midnight to 8 a.m.) with night lighting (mostly red and varying from 5 to 220 lux)	2 months	Associations between sleep and psychological measures ; no sleep disorders ; no modifications of feelings of fatigue ; no signs of depression, anxiety or vigour
Spaceflight-Associated Brain White Matter Microstructural Changes and Intracranial Fluid Redistribution	Lee JK, Koppelmans V, Riascos RF, Hasan KM, Pasternak O, Mulavara AP, Bloomberg JJ, Seidler RD	2019	Spaceflight	International space station	N/A	N/A	N/A	N/A	1 to 6 months	White matter structural connectivity changes in the cerebellum, corticospinal tract, and the superior longitudinal fasiculus ; association between brain

										changes and postural balance declines
Specificity of Sleep–Wakefulness Cycle during a 105-Day Isolation	Kovrov GV, Rusakova IM, Shvarkov SB, Posokhova SI, Posokhova SS, Ponomarevab IP	2010	Spaceflight simulation	Mars 105	N/A	N/A	N/A	N/A	3 months	Episodic alteration of structural organization of sleep ; sleep stages and phases stable
Stress and Recovery Responses during a 105-day Ground-based Space Simulation	Nicolas M, Gushin V	2014	Spaceflight simulation	Mars 105	Institute for Biomedical Problems of Moscow (Russia)	550 m3	Four hermetically sealed interconnected habitat modules: principal living quarters (kitchen-dining room, iving room, main control room, toilet, six individual rooms with a bed, a desk, a personal computer, a chair and shelves for personal belongings), medical (routine medical and telemedical	Modules under conditions of artificial atmospheric environment at normal barometric pressure	3 months	No stress overload and impaired psychological states

							examinations, laboratory, diagnostic investigations and isolation), storage (food storage room, experimental greenhouse, bathroom, sauna, gym), and one external module used to simulate the 'Martian surface' (three bunk beds, two workstations, toilet, control and data collection system, video control and communicatio ns)			
Study of individual and group affective processes in the crew of a simulated mission to Mars: Positive affectivity as a valuable indicator of changes in the crew affectivity	Šolcová I, Lačev A, Solcova I	201 4	Spacefligh t simulation	Mars 500	N/A	N/A	N/A	N/A	17 months	Different patterns of adaptation ; decrease positive emotions

The impact of long-term confinement and exercise on central and peripheral stress markers	Jacubowski A, Abeln V, Vogt T, Yi B, Choukèr A, Fomina E, Strüder HK, Schneider S	2015	Spaceflight simulation	Mars 500	N/A	N/A	Four connected habitat modules (medical module, habitable module, storage module and Mars landing module) and one external module, simulating the Martian surface	N/A	17 months	Decrease cortical activity ; increase cortisol level
The NASA Twins Study: A multidimensional analysis of a year-long human spaceflight	Garrett-Bakelman FE, Darshi M, Green SJ, Gur RC, Lin L, Macias BR, McKenna MJ, Meydan C, Mishra T, Nasrini J, Piening BD, Rizzardi LF, Sharma K, Siamwala JH, Taylor L, Vitaterna MH, Afkarian M, Afshinnekoo E, Ahadi S, Ambati A, Arya M, Bezdan D,	2021	Spaceflight	International space station	N/A	N/A	N/A	N/A	11 months	Cardiovascular, neuro-ocular and cognitive function changes

Callahan CM,
Chen S, Choi
AMK,
Chlipala GE,
Contrepois K,
Covington M,
Crucian BE,
De Vivo I,
Dinges DF,
Ebert DJ,
Feinberg JI,
Gandara JA,
George KA,
Goutsias J,
Grills GS,
Hargens AR,
Heer M,
Hillary RP,
Hoofnagle
AN, Hook
VYH,
Jenkinson G,
Jiang P,
Keshavarzian
A, Laurie SS,
Lee-
McMullen B,
Lumpkins SB,
MacKay M,
Maienschein-
Cline MG,
Melnick AM,
Moore TM,
Nakahira K,
Patel HH,
Pietrzyk R,
Rao V, Saito
R, Salins DN,
Schilling JM,

	Sears DD, Sheridan CK, Stenger MB, Tryggvadottir R, Urban AE, Vaisar T, Van Espen B, Zhang J, Ziegler MG, Zwart SR, Charles JB, Kundrot CE, Scott GBI, Bailey SM, Basner M, Feinberg AP, Lee SMC, Mason CE, Mignot E, Rana BK, Smith SM, Snyder MP, Turek FW									
The tougher the environment, the harder the adaptation? A psychological point of view in extreme situations	Nicolas M, Martinent G, Suedfeld P, Palinkas L, Bachelard C, Gaudino M	2021	Polar station	Amsterdam station & Concordia	37°S (Amsterdam station), 75°S (Concordia)	55 km2 (Amsterdam station)	N/A	Amsterdam station is located on a smal island with a pure air, an Oceanic climate, a temperature of 14°C on average, persistent winds, high levels of humidity, different spacies of native birds, seals, grasses. This station hosts 25 individuals in	12 months	Evolution of psychological adaptation dependant of the characteristics of the polar environment ; perceived control impact psychological adaptation processes

								winter and 50 in summer. Concordia is one of the four permanent station located on the High plateau. This is one of the coldest, windiest, and driest place on Earth with no fauna and flora. The temperature is on average -53°C, and can drop to -84.6°C with a low level of humidity. The altitude is 3 232 m, 656 hPa. Crews hosted are multicultural and come from diffrent nations		
Time Effects, Displacement, and Leadership Roles on a Lunar Space Station Analogue	Wang Y, Wu R	2015	Spaceflight simulation	Lunar Palace	Beihang University (China)	100 m2	One comprehensive cabin (42 m2) and one plant cabin (58 m2) with four private bedrooms, a living room, a restroom, and a room for waste disposal and insect culturing	Bedrooms were very small, contraining a single bed, a small table, and a door. There were only private areas where they could connect to the Internet using their personal laptop or smartphone. No outgoing calls were available	2 months	Mood states changes ; increase fatigue ; no evidenc eof the third quarter phenomenon

								with cell phones (only one wired phone available)		
Two year follow-up study of stressors and occupational stress in submariners	Brasher KS, Sparshott KF, Weir AB, Day AJ, Bridger RS	2012	Submarine	N/A	N/A	N/A	N/A	N/A	N/A	Different predictors (i.e., over-commitment and rank for submariner; length of service, body mass index, physical work for other marins) despite a similar prevalence of occupational stress
Vegetative regulation of blood circulation in the Martian crew individuals in the Mars 500 project to Mars	Bersenev EY, Rusanov VB, Chernikova AG	2013	Spaceflight simulation	Mars 500	N/A	N/A	N/A	Work and rest schedule of the crew similar to that used in space (i.e., 7 day week with two days-off). The activities included: basic operations and procedures (e.g., medical monitoring & control over the health, physical training procedures, inspection and	17 months	Multistage adaptation highlighted by HRV (i.e., HR, pNN50, SI) ; functional states unchanged ; adaptation efficiency

								maintenance of the equipment systems, control of the Mars landing module, conduction of scientific investigations, completion of sanitary and hygienic procedures). The crew operated in the artificial atmospheric environment at normal barometric pressure		
Work content influences on cognitive task load, emotional state and performance during a simulated 520-days' Mars mission	Cohen I, den Braber N, Smets NJJM, van Diggelen J, Brinkman W-P, Neerincx MA	2016	Spaceflight simulation	Mars 500	N/A	N/A	N/A	N/A	17 months	Alterations of cognitive task load and emotional state levels ; association between cognitive, affective factors and task performance

Depuis ses origines, le progrès technique et scientifique expose l'homme à des situations extrêmes et à des milieux hostiles. Depuis les origines, la tension psychologique, l'épreuve physique et leurs conséquences pour la santé, voire leur risque de séquelles sont présentes dans cette longue marche. C'est un nouveau pan de l'histoire qui s'ouvre avec les LDSE. Il comporte dans sa dimension physique comme dans sa dimension médico-psychologique des éléments nouveaux avec en première place l'exposition prolongée à l'apesanteur. Ils comportent également des contraintes déjà prises en compte comme l'isolement et confinement associés à la promiscuité, au manque d'intimité, au danger. Ces contraintes sont caractéristiques d'environnements analogues dans lesquels travaillent les sous-mariniers et des hivernants polaires. Dans le cas des astronautes, il convient de considérer en plus une intrusion permanente du contrôle de mission par l'agence spatiale responsable et une extrême visibilité pour l'un univers extérieur à la fois proche et inaccessible que constitue la terre. Autant de stresseurs qu'il convient d'étudier car ayant un impact non négligeable pour les missions de demain. En effet, dans un vol habité la maitrise du facteur humain revêt une importance plus stricte que partout ailleurs. La moindre erreur n'est pas envisageable au risque du péril de la mission et finalement, la limite est mince entre l'échec et le succès. De plus, l'autonomie dont devront faire preuve les astronautes dans les vols lointains ajoutera un stresseur supplémentaire ; la solitude pourra se faire très pesante notamment lors des prises décisions difficiles que constitueront les imprévus et cas non-conformes. Longtemps mis de côté par la NASA, les facteurs de stress, et plus particulièrement les acteurs de maintien de la santé mentale des astronautes sont devenus un enjeu central dans l'élaboration des prochains longs voyages. Pour autant, très tôt l'agence spatiale soviétique avait pris en compte cet élément, probablement car les voyages spatiaux avaient déjà un caractère temporel plus long dès 1954. Les environnements analogues ont apporté à la communauté scientifique des connaissances essentielles pour mieux apprivoiser les enjeux des voyages spatiaux de longue durée tout en soulignant qu'il demeure de nombreux enjeux scientifiques. Même si les astronautes sont soumis à une sélection sévère et à un entraînement long, la durée des séjours dans l'espace augmentant ainsi que l'hétérogénéité des équipages, les situations de stress sont difficilement évitables obligeant la communauté à penser et valider des contre-mesures toujours plus performantes et adaptées à la diversité des temps dans la mission et au fonctionnement de chacun des astronautes. Il s’agit d’un véritable challenge que de pouvoir maintenir la réponse adaptative dans sa dynamique au décours des missions à venir.

Synthèse des résultats principaux

La revue de littérature (PRISMA) que nous avons engagé avait trois objectifs principaux : (1) de résumer la littérature sur l'impact des ICE/EUE sur l'adaptation humaine à partir d'un cadre pluridisciplinaire physiologique, biologique, neuroscientifique, comportemental, cognitif et psychologique ; (2) d'identifier les processus psychocognitifs et les mécanismes neuronaux que les professionnels développent pour s'adapter à ces environnements exceptionnels ; et (3) d'étudier les différences et similitudes entre les analogues spatiaux en termes de leurs impacts sur l'adaptabilité humaine.

Nos résultats mettent en évidence le besoin de reconsidérer la liste des analogues spatiaux en vue des prochaines missions spatiales de longue durée (LDSE). Cette revue fait appel à des champs de connaissance et disciplinaires différents et permet d'ériger des ponts à plusieurs niveaux sur la question de l'adaptation humaine. L'espace et ses environnements analogues induisent des effets aussi bien pathogéniques que salutogéniques. De nombreux résultats mixes sont décrits dans la littérature, et ne permettent d'établir un véritable consensus. Une des raisons est notamment l'importante hétérogénéité des méthodologies de recherche et des outils employés. De plus, nos résultats insistent sur la nature complexe et multifactorielle de l'adaptation qui induit une grande variabilité inter-individuelle. Ce constat rend délicat la définition de mécanismes psychocognitifs et neuronaux sous-jacents au processus d'adaptation. Enfin, il pointe le manque de données disponibles quant aux mécanismes de récupération, alors même que la succession des missions pour un même astronaute fait partie des possibles.

Synthèse du chapitre I

Depuis les premières expéditions polaires où les aventuriers se confrontaient bien souvent à la mort, il est indéniable que les conditions de vie ont beaucoup évolué. Nous avons pu démontrer que les articles publiés majoritairement avant 2005 font état d'un effet pathogénique de l'environnement sur l'état de santé des équipages. Progressivement et sous l'impulsion des travaux de Palinkas et Suedfled (Palinkas & Suedfeld, 2008 ; Palinkas & Suedfeld, 2021), habiter les extrêmes peut recouvrir des effets bénéfiques. Ce constat a insufflé une nouvelle dynamique à la recherche, les équipes de recherche ne tentant plus de se focaliser exclusivement sur une éventuelle dégradation mais en cherchant à identifier une stabilité voire explorer une amélioration de l'adaptation. En effet, il est d'une importance majeure de signaler les non-changements qui pourraient être des signes d'adaptation.

De nombreuses évolutions restent primordiales dans les méthodologies de recherche pour aller de l'avant et permettre d'étudier l'adaptation sous tous ses aspects. L'avenir de la recherche implique ainsi d'acquérir une vision intégrative pour permettre de comprendre les mécanismes adaptatifs dans leur entièreté. Il n'y a que de cette manière que nous pourrons maintenir, voire renforcer, les ressources des membres présents dans ces milieux hors du commun mais aussi sélectionner de manière appropriée les équipages.

Un premier point pour y arriver est de poursuivre l'étude de l'impact des environnements analogues à l'espace sur l'adaptation pour mieux en comprendre les mécanismes. Cet objectif est poursuivi au sein du chapitre suivant qui propose une approche la plus holistique possible en ciblant des réponses psychologiques, physiologiques, cognitives et sensorielles lors de missions au sein de plusieurs analogues à l'espace.

CHAPITRE II

Impact des environnements analogues : L’être humain au bout du monde

Le plus bel objectif que le genre humain
se puisse fixer n’est pas la poursuite d’une chimère
consistant à réduire l’inconnu à néant :
ce n’est que l’effort inlassable pour déplacer
les frontières de l’inconnu un peu plus
au-delà des limites de sa propre sphère d’activité

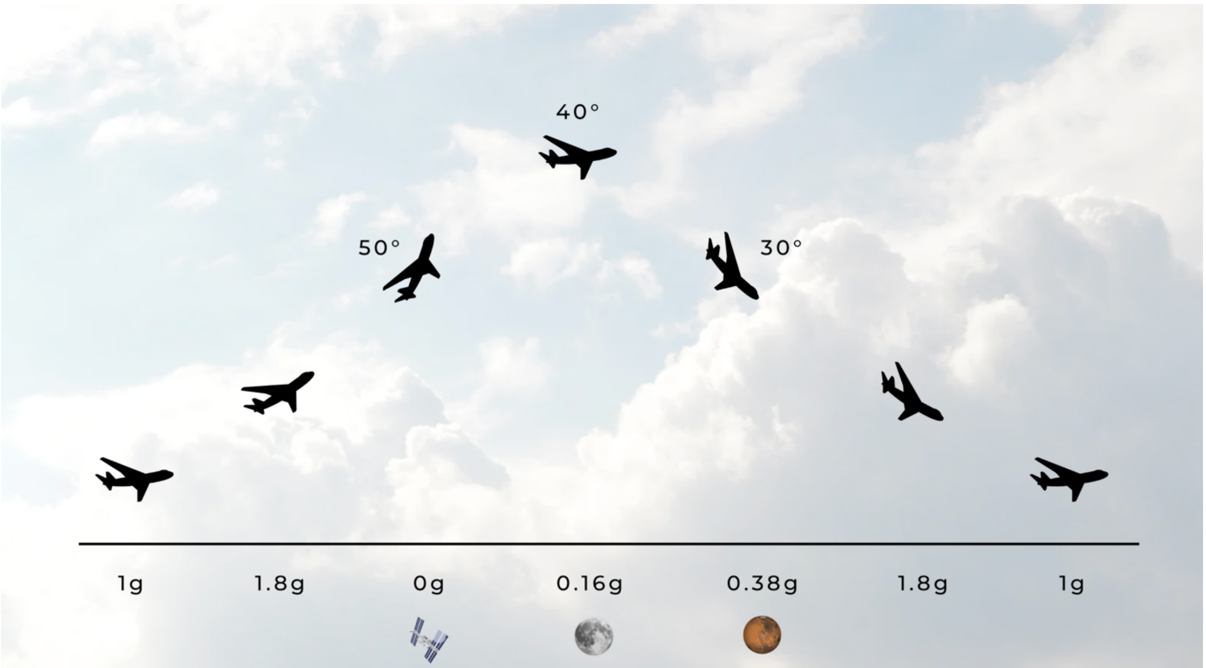
Aldous Huxley

L'étude des effets de la microgravité sur l'organisme a largement été documentée au sein de la littérature scientifique pour comprendre le déconditionnement qui en résulte, qu'il soit musculaire, osseux, ou cardiovasculaire pour ne citer que les plus connus. Récemment, il existe un intérêt croissant pour évaluer l'impact de la gravité partielle lunaire et martienne en raison de l'orientation des prochaines missions spatiales. Or, avec le développement du tourisme spatial, le paysage des vols spatiaux est en proie à de profonds changements et de nouveaux challenges. Les trajets au-delà de nos frontières terrestres seront amenés à être plus nombreux, et des personnes qui jusqu'alors ne pouvaient que contempler le ciel les pieds sur Terre pourront vivre l'expérience de s'y déplacer pour l'observer de l'intérieur. Ce constat nous rappelle que l'être humain n'est pas adapté à un milieu tel que l'espace, et ne peut survivre sans une technologie de haut niveau. Les répercussions sur l'organisme ont déjà été renseignées chez les astronautes lors de missions allant de quelques jours à un an ceux chez les futurs équipages de touristes spatiaux seront inévitables d'autant qu'ils moins voire peu sélectionnés et entraînés. Pour autant, aucune étude ne s'est à ce jour focalisée sur l'impact des changements répétés de gravités incluant la microgravité et la gravité partielle sur les réponses psychologiques, cognitives, physiologiques et sensorielles de tout un chacun, candidat possible à un voyage spatial. De nombreuses questions sont dès lors soulevées : quelles sont les capacités d'adaptation physiologiques, sensorielles, psychologiques et cognitives d'un individu tout venant ? Sa santé sera-t-elle impactée à court, moyen ou long terme par les vols spatiaux ouverts pour le tourisme spatial ? Si oui, à quel niveau ? Quels profils d'individus pourront faire partie des équipages de touristes spatiaux ? Faut-il prioriser certaines caractéristiques basées sur un état de base physiologique, le niveau de ressources psychologiques et/ou sur des performances cognitives ? Quelle préparation minimum doit être requise pour permettre au minimum le voyage et une adaptation acceptable de l'organisme à la contrainte ?

Apporter des réponses précises à ces questions reste complexe en collectant des données issues des vols spatiaux. La revue de Le Roy et al. (2023) souligne l'importance de s'appuyer sur des environnements analogues. Afin de préparer les équipages d'astronautes « touristiques » à aller dans l'espace depuis la Terre, un des moyens permettant de récréer la microgravité (i.e., élément indispensable pour étudier son impact à court et long terme) est l'utilisation des vols paraboliques. Impulsée par les États-Unis, la France dans ce domaine en est l'une des nations pionnières. Initiées avec la Caravelle

VI-R des années 1989 à 1995, puis avec l'Airbus A300 Zero G des années 1996 à 2014, et l'Airbus A310 Zero G depuis 2015, ce sont à ce jour des centaines de campagnes de vols paraboliques effectuées et une mobilisation de milliers de scientifiques pour recréer un véritable laboratoire volant. En pratique, la microgravité est un état au cours duquel tout objet n'est plus soumis aux lois de la gravité via la force d'attraction terrestre. Chaque objet donne alors l'impression de « flotter » dans l'espace, en raison de l'absence de force de gravité. Un vol parabolique permet ainsi de recréer une succession de périodes en microgravité, par une succession de manœuvres spéciales dites « manœuvres paraboliques ». Il s'agit de la formation d'un arc d'ellipse ou parabole composée d'une phase d'hypergravité à 1.8 g (i.e., entrée en parabole, *pull up*), suivie d'une phase de microgravité en 0 g ou gravité partielle en 0.16 g ou 0.38 g (i.e., parabole, *injection*), et d'une phase à nouveau d'hypergravité à 1.8 g (i.e., sortie de parabole, *pull out*). La manœuvre parabolique est présentée Figure 16. Dans le cadre actuel des campagnes, 31 paraboles sont réalisées, soit 31 périodes en microgravité.

Figure 16
Manœuvre parabolique



Afin de pouvoir répondre à certains des enjeux que posent le tourisme spatial, nous avons proposé un projet centré sur l'adaptation des « touristes spatiaux » aux contraintes gravitaires répétées qui a été sélectionné pour être conduit sur deux campagnes de vols paraboliques de l'Agence spatiale européenne (*European space agency*, ESA) : la 79ème campagne de vols paraboliques en microgravité et la 81ème campagne de vols paraboliques en gravité partielle. Dans le cadre de cette thèse, seule les résultats issus de la campagne de vols en microgravité seront présentés (étude ENACT).

L'étude ENACT avait trois objectifs principaux : (1) investiguer l'impact des changements répétés de gravités incluant la microgravité sur les réponses psychologiques, physiologiques et sensorielles de sujets non-astronautes ; (2) évaluer la récupération à une semaine post vol ; et (3) évaluer la pertinence d'un fonctionnement parasympathique élevé en tant que biomarqueur d'adaptation pour des individus n'ayant pas suivi de sélection autre que l'aptitude médicale, ni d'entraînement aux contraintes de l'espace.

La 79ème campagne de vols en microgravité a rassemblé des scientifiques, médecins, ingénieurs, coordinateurs académiques à la fois primo-volants (i.e., aucune expérience de vols paraboliques) et volants (i.e., ayant effectués jusqu'à 30 vols paraboliques). Ce choix de population visait à cibler des membres d'équipage susceptibles de reproduire l'hétérogénéité des équipages pour le tourisme spatial, incluant des experts et des sujets totalement naïfs.

Nous posons l'hypothèse que les vols paraboliques induisent un impact psychophysiologique et sensoriel, notamment chez le profil de non professionnels ayant un fonctionnement parasympathique plus faible avant le vol. Un fonctionnement parasympathique basal élevé devrait ainsi constituer un marqueur d'adaptation et de récupération plus efficiente.


Air Zero G
weightless with Novespace
E7
Electrical Panel No. 7

Effect of Repeated Gravity Changes during Parabolic Flights:

Evidence of the Need to Assist Space Tourist to Outer Space

En révision[7]

[7] Le Roy, B., Martin-Krumm, C., Beauchamps, V., Jimenez, A., Giaume, L., Jacob, S., Voilque, A., Ferhani, O., Altena, E., & Trousselard, M. Effect of Repeated Gravity Changes during Parabolic Flight: Evidence of the Need to Assist Space Tourists to Outer Space. *PLoS ONE.*

Abstract

Introduction. In the era of space tourism, walking in the steps of Neil Armstrong has never been more real. Future space tourists will have to face the harshness of the environment, especially the travel, and adapt quickly for their own safety. This issue raises both the question of preparation and the impact of such a journey on novice populations who have not been selected for their physical and cognitive abilities. Thus, the objectives of the study are (1) to investigate the impact of a travel on psychological, physiological, and sensory responses using a parabolic flight experience including repeated changes in gravity; (2) to assess recovery from this experience one week later; and (3) to evaluate the relevance of a high parasympathetic functioning as a biomarker of adaptation for subjects unaware of any selection and spatial training.

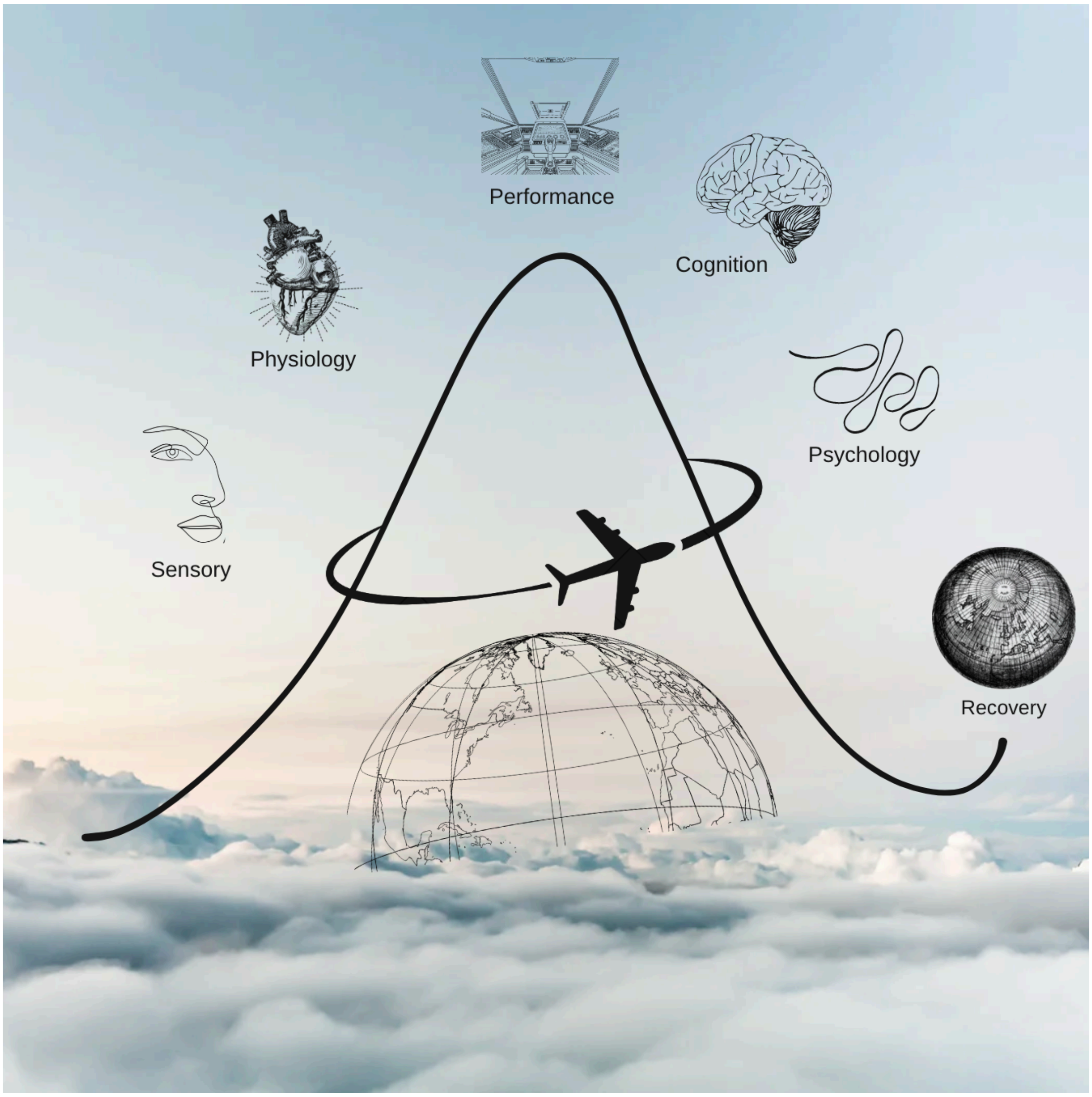
Method. Seventeen healthy participants were enrolled in the 79^{th} ESA Parabolic Flight Campaign on board the Airbus A310. Psychological, physiological, and sensory responses were measured the day before the 3h-flight (baseline), on the morning before boarding (pre-f), on the afternoon after landing (post-f), the tomorrow morning (recovery, D+1) and one week after the flight (recovery, D+7). Flyers were allocated to two groups according to their parasympathetic activation (RMSSD) at baseline: high parasympathetic (HP profile) and low parasympathetic (LP profile).

Results. At the psychological level, HP profile have a high coping acceptation. Moreover, they have a higher level of interoceptive awareness than LP profile. On the opposite, they voluntarily tend to ignore or distract themselves from sensations of pain or discomfort and have a poorer quality of sleep compared to LP profile. At the exteroceptive level, they have a better identification of odors in postflight. Proprioception is damaged in both profiles with a decrease in postural stability, particularly during visual deprivation. Nevertheless, the HP profile highlight a predisposition to a more adaptive postural response. At the physiological level, flyers have a better postflight heart rate variability in both linear and non-linear components (i.e., RR intervals, SDNN, RMSSD, pNN50, HF, SD1, SD2, SD ratio, $\alpha 1$, sample entropy), especially the HP profile (i.e., SDNN, RMSSD, pNN50, HF, LF, SD1, SD2, $\alpha 2$). At recovery, subjects have a strengthening of their resources at D+1 and D+7, and a better postural awareness at D+1 and sleep quality at D+7. Nevertheless, our results

reveal a critical period characterized by a major challenge. From the day after the flight (D+1), flyers voluntarily tend to ignore or distract themselves from sensations of pain or discomfort. They have a significant drop in positive affect and a significant increase in negative affect at D+1 and D+7. This is particularly true for HP profile compared to LP profile. Although flyers reported better subjective sleep quality (i.e., except for the HP profile), they encounter an increase in wake-up during the night and a lower sleep duration at D+1.

Conclusion. These results raise the question of the risks that may be induced by space tourism. They highlight two major outcomes: (1) the travel of future space tourists does not seem to be at risk as long as the individuals are in good health (e.g., without any pathology that would make them unfit for flight); (2) the need to take care of the crews over several days and/or to include in the preparation a module allowing them to be prepared for the postflight period and the return to life on Earth. Beyond this, these results contribute to enriching our knowledge of the real human challenge of confronting the constraints of space travel.

Figure 17
Graphical abstract ENACT



Keywords

Adaptation, Health, Neurosciences, Parabolic flight, Performance, Space tourism

1. Introduction

Since the dawn of time, anyone who looks at the stars has aspired to touch them. With the advent of space tourism, many humans will soon be able to go beyond the boundaries of the Earth to see space with their own eyes. Spaceflight is associated with many physiological, sensory, and psychological effects that may lead to disturbances and impact the health and safety of crews. Considering that an astronaut requires several years of preparation to go into space, it seems urgent to understand the impact to send an average individual out of the planet. Actually, space tourists will no more be selected for their physical and mental abilities, but for their desire to confront themselves to the limits of the Earth's atmosphere. Antuñano and collaborators [1] listed six domains/consequences that may occur during a tourist flight: inflight medical emergency, inflight death, alteration of health and security of passengers, compromise the protective equipment, emergency procedures, and jeopardize the safety of the flight. These risks start at the beginning of the space travel by taking into account the displacement from the Earth, i.e., the journey. This challenge raises the question of the impact of flight on tourists' adaptation during the space experience and over on their health after it.

In space, the relationship to one's own body or to other floating bodies, the altered perception of one's environment and temporal reference points, the pleasure of friction in the extreme conditions of the vacuum of space provoke psychological, physiological, and sensory changes that profoundly affect the human connection to space. This environment can impair the performance of astronauts due to stressors related to the environment and the mission [2–7]. Astronauts implement conservative regulations to maintain homeostatic status, especially physiological, due to the surrounding gravitational environmental factor. This physiological impact of the gravitational environment is not isolated. The studies focusing on the impacts of space or space analogs can provide first elements of understanding and response to the challenges faced by humans in the space unusual environments. They are characterized by extreme climates, danger, limited facilities and supplies, isolation from loved ones and the need to interact with others. Data from historical and analogous spaceflights suggest that prolonged periods of social and sensory monotony can have a pathological impact on human functioning, including psycho-cognitive and sensory responses (e.g., psychosocial health, decreased cognitive performance, decreased ability to regulate emotions, as well as increased vulnerability to negative emotions, sleep disturbance) although a salutogenic response has been increasingly demonstrated [8–12].

Nevertheless, recent launching from private compagnies (i.e., Blue Origin, Virgin Galactic, Space X, Axiom Space) have change the rules of spaceflights, opening the way for space tourism. Competitiveness is at an all-time elevated to secure a place in this market share, where the average entry ticket for launch is $1,000,000 [13]. In suborbital spaceflight, environmental factors (e.g., microgravity, accelerations, vibrations, cabin pressurization) may worsen previous pathologies or generate high levels of stress [1]. Antuñano and collaborators [1] cited different pathologies that may be of concern including psychiatric disorders, neurological disorders, sleep disturbances, addictions, cognitive impairments, vision, and hearing disabilities. This may lead to an alteration of the behavior and performance of crews, resulting in an inability to operate efficiently for emergencies and to communicate effectively with the ground. Surprisingly, there is little emphasis on the impact of the journey itself.

The parabolic flights to study preparation to manned space missions is relevant, especially for the spatial tourism journey. The main interest of parabolic flights is twofold: on the one hand, to perform verification tests before space experiments to improve their quality and success rate, and after a space mission to confirm or invalidate the results obtained during space experiments; and on the other hand, by providing a laboratory in which the level of gravity can be varied. Periods of weightlessness (0g) are combined with periods of normal gravity (1g), and hyper-gravity (1.8g). The literature has for many years emphasized the relevance of parabolic flights in order to better understand how the organism is able to adapt to this hostile environment, in particular to microgravity [14–19]. Parabolic flights induce a high psychological and physiological strain on flyers [20]. The impacts are cerebral [6], bony [21], ocular [22] and cardiovascular [4, 23, 24]. Studies have focused on specific physiological [25, 26], cerebral [27, 28] and sensorial aspects [29, 30]. More specifically, the project by Moser and Voica [31], which took place over several sessions, studied the adaptation of the vegetative nervous system before, during and after parabolic flights. Other projects have been carried out in the same years to evaluate the effect of microgravity on the cardiovascular system [32–34]. These projects are still relatively longstanding and answered the questions asked by showing that variations in heart size occur even during short periods of microgravity, and that some of the results concerning heart rate and aspects of the modulation of cardiovascular function by the autonomic nervous system are similar to those observed during longer periods of spaceflight. More recently, Wollseiffen and collaborators studied cerebrovascular autoregulation as a determinant of neurocognitive performance [35, 36]. Brummer et al. [37] confirm that parabolic flights induce a stress response that impact physical states, cognition, and stress hormone release. Furthermore, Schneider et al. [38] have shown an association between stress hormone release, psychological and physical responses. Also, they show an association between the level of stress and mood. Other authors reveal an alteration of cognitive performance on flight [39, 40], notably attentional processes [39]. Thus, it is not clear if phases of weightlessness induce lower performance. Psychophysiological, and cognitive responses need to be addressed to evaluate the impact of these factors on individual. More recently, Collado and collaborators [41] investigated the impact of parabolic flights between maladaptive and adaptive groups (i.e., differentiated by their sensitivity to motion sickness) on psychological states. Their results show that the maladaptive group have disturbances to integrate sensory information and to regulate mood that led to difficulties in coping with the physical demands of the environment. Affective responses are likely to impact cognitive, physiological, and sensory functioning. Such studies did not show an alteration of recovery and highlight that individuals recover immediately after landing [38, 39].

Therefore, when considering future space travels, much of this research would not be complete without studying the integration of bodily information and its consequences in terms of emotional and cognitive, physiological, and sensory responses. These interactions between the body and the environment play a fundamental role in how individuals act on their environment and cope with changes in psychological, sensory, and cognitive performance [42, 43]. These interactions are the basis of the adaptive ability that allows us to react appropriately in a constantly changing environment. If we consider this interrelationship between the body and the environment to be at the heart of adaptive capacities, it must be noted that there is significant inter-individual variability [8, 44]. In particular, the literature highlights related individual characteristics as candidate factors for understanding stress adaptation mechanisms. One of these is physiological and is based on the flexibility of the parasympathetic system at rest, measured by recording heart rate variability (HRV) [45–47]. This parasympathetic system is involved in stress regulation and participates in the individual's adaptive response to external changes [48, 49]. HRV is an indicator of psychological and physiological stress, known to reflect both the parasympathetic and the sympathetic branches of the autonomous nervous system (ANS) [45]. Sympathetic and parasympathetic influences are evaluated by variation in the interval between successive heartbeats (i.e., RR interval) [50, 51]. Vagally-mediated HRV is commonly indexed by the root mean square of successive differences (RMSSD), and high-frequency (HF) [52, 53]. Moreover, interoception may underline the relationship between cardiac and exteroceptive biosignal responses [54, 55]. Le Roy et al. [48] have shown that cardiac biosignal profiles lead to different adaptation throughout a patrol on board a nuclear submarine. They showed that the differences in terms of interoception and exteroception have an impact on the health of submariners.

Then, on one hand, parabolic flights offer experimental conditions of repeated gravitational changes, relevant for studying the functioning of subjects unaware of any selection and spatial training during a space travel. On the second hand, few studies have explored the impact of repeated gravity changes on the body-environment relationship. This impact on health for non-astronaut population remains unknown. This is a real challenge for the ambition of space tourism. Thus, we conducted a study on subjects unaware of any selection and spatial training with the following objectives: (1) to investigate the impact of repeated changes in gravity, including microgravity, on psychological, physiological, cognitive, and sensory conditions; (2) to assess recovery from a parabolic flight experience one week later; and (3) to evaluate the relevance of a high parasympathetic functioning as a biomarker of adaptation for subjects unaware of any selection and spatial training.

2. Materials & Methods

2.1. Design

The present study (ID-RCB: 2022-A01317-36) was approved by the Committee for the Protection of Individuals (CPP Ile de France XI, Montigny-le-Bretonneux, France) and was conducted according to the standards of the Declaration of Helsinki. After comprehensive verbal and written presentations, all participants gave their written consent to participate.

2.2. Participants

Health status of participants was confirmed by the delivery of a parabolic flight medical aptitude certificate as well as a clinical history and examination at the inclusion.

Participants were healthy scientifics (n = 7), physicians (n = 5), academic coordinators (n = 3), engineers (n = 2), and other (n = 1). Their health status was confirmed by the delivery of a parabolic flight medical aptitude certificate as well as a clinical history and examination at the inclusion. One participant (from the scientific team) was excluded for medical reasons, leaving 17 subjects (four women and 13 men). The average age is 41.35 ± 8.95, ranging from 27 to 61 years. Among the four women, one (25.00%) was using contraception (i.e., a copper intrauterine device). None of the participants were taking medication or smoke. Two (11.76%) had rip replacement or suffered from deafness in right ear since the age of ten. Average height is 177.35 ± 6.83 meters, and weight is 69.71 ± 9.06 kilos. Everyone is in couple and nine (52.94%) have children. 12 (70.58%) reported to having encountered personal (2.66 ± 1.37) or/and 10 (58.82%) professional (6.00 ± 5.04) major stressful events.

Six (35.29%) already experienced extreme environments (e.g., survival at sea, expeditions in remote locations, mission in Antarctica, life simulation on Mars). 10 (58.82%) never experienced parabolic flight campaign, three (17.64%), and four (23.52%) have an at least 30 parabolic flights and could be considered as regular space tourists.

Table 1 reports sociodemographic characteristics.

Table 1

Socio-demographic characteristics of participants

Measurements	Microgravity data*
N	17
Mage	41.35 ± 8.95
Mheight	177.35 ± 6.83
Mweight	69.71 ± 9.06
Gender (women/men)	23.52%/76.47%
In couple/with children	100%/52.94%
Contraception	25.00%
Clinical medical history (i.e., hip replacement, deafness)	11.76%
Personal major stressful events	2.66 ± 1.37
Professional major stressful events	6.00 ± 5.04
Previous experience in extremes	35.29%
Parabolic flight experience (novice/beginner/expert)	58.82%/17.64%/23.52%

*Mean and standard deviation are reported when necessary. Other figures show the ratio of the number of subjects.

2.3. Data collection

2.3.1. Subjective measurements

A 20-item sociodemographic questionnaire was developed to collect general information on the participant's family situation, medical history, current health status, hobbies, familiarity with extreme environments and parabolic flights.

Psychology. The Coping Flexibility Scale (CFS) assesses coping flexibility defined as the ability to interrupt an ineffective coping strategy (i.e., evaluative coping) and to generate/implement an alternative coping strategy (i.e., adaptive coping) (10 items) [56]. The Freiburg Mindfulness Inventory (FMI) evaluates mindfulness disposition (14 items) [57]. The scale is divided into two sub-factors that measure presence and acceptance without judgment. Multidimensional Assessment of Interoceptive Awareness (MAIA) evaluates interoceptive awareness (32 items) [58]. The scale is divided into eight sub-factors that measure awareness of uncomfortable, comfortable, and neutral body sensations, the response to sensations of pain and discomfort, the ability to regulate attention to body sensations, and awareness of mind-body integration (i.e., noticing, not distracting, not worrying, attention regulation, emotional awareness, self-regulation, body listening, trusting). The Scale of Positive and Negative Experience (SPANE) assesses subjective feelings of positive and negative affect, based on how frequently they were felt over the previous four weeks (12 items) [59]. The scale is divided into two-subfactors that measure positive and negative emotions. The scale is divided into two sub-factors: positive and negative affect. The Sleep Quality Scale (SQS) measures sleep quality (1 item) [60]. The Perceived Stress Scale (PSS) assesses the subjective stress level (14 items) [61].

Extrasensors. The Postural Awareness Scale (PAS) assesses mind-body awareness, divided into two sub-factors that measure ease/familiarity with postural awareness and need for attention regulation with postural awareness (20 items) [62].

2.3.2. Sleep activity

Sleep nights were recorded the night before and the day after the flight using an actimeter (MotionWatch 8, CamNtech, Texas, USA). This device monitor sleep, circadian rhythms, and physical activity. The most known values were used such as Wakefulness After Sleep Onset (WASO). A sleep diary was completed on awakening to collect subjective information on the subjective quality of the night spent (i.e., well resting waking up, repetitive thoughts, physical indicators of stress, vivid dreams, frequency of waking up).

2.3.3. Exteroceptive measurements

Olfaction. The European Test of Olfactory Capabilities (ETOC) assesses olfactory sensitivity. Individuals are asked to select a bottle (there are 16 sets of four bottles) that contains a specific odor (a discrimination task) and state the nature of this odor (an identification task) [63]. In our experiment, participants were also asked to evaluate the hedonic value of the detected odor to complement the ETOC.

Proprioception. Posturography was assessed using a stabilometric static platform (Stabilotest). The acquisition frequency is 40 Hz. Subjects were asked to stand for one minute with their eyes open, and for one minute with their eyes closed. Among the numerous metrics used to characterize postural stability reported in the literature (Takagi et al., 1985; Winter et al., 1990), we assessed the most frequent measures: elliptic surface (mm^2); LFS (i.e., length ratio of the surface, mm^{-1}); asymmetries using logarithm (mm) along sagittal (antero-posterior) and frontal (medio-lateral) planes; slope (degree); average speed (mm/s); variance speed (mm/s) ; NA02 (i.e., maximum distance covered by the center of pressure).

2.3.4. HRV

Heartbeat interval data (RR) were recorded for a ten-minute period, with subjects in a sitting position. The cardiac biosignal was recorded using a Polar H10 pectoral chest belt (Polar, Finland), at a sampling frequency of 180 Hz. The literature confirms the reliability of the Polar H10 belt to measure HRV [66–70], and its use has been validated in a military population [71]. Furthermore, it has been shown to be as accurate as a reference ECG at rest, and during exercise [72]. This device's low artifact rate makes it the best-available portable tool for recording cardiac activity, especially in studies in ecological environments. Three sensors pick up electrical signals from the heartbeat, which are sent in real time, via Bluetooth, to a software application [73].

The HRV analysis followed guidelines reported in [46, 74], which take into account potential circadian variation, and used the *PyHRV* python library [75]. The following data were recorded: weight; height; waist-to-hip ratio; smoking habits; most recent alcohol intake (>24h); most recent caffeinated (coffee/ tea) intake (>1h); most recent meal (>2h); most recent physical activity (>12h); and quality of sleep on the day of the experiment and the preceding day.

Raw ECG data were filtered between 3 and 45 Hz using a finite impulse response band-pass filter. The order of the filter was set at 54 (0.3 times the sampling frequency). R peaks were automatically detected using the *BioSPPy* python library [76]. A Hamilton segmentation was performed on the filtered signal, followed by R-peak correction with tolerance set to 0.05. R-waves were manually examined to ensure correct detection. If an ECG sequence was overly noisy when visualizing the superposition of all QRS complex, the time interval was manually removed to improve data quality. RR intervals were automatically detected with the *hrvanalysis* module using linear interpolation, and manually corrected for artifacts and ectopic beats.

Time domain analysis. Time domain HRV metrics included mean RR (the mean interbeat interval), SDNN (Standard Deviation of the Normal-to-Normal RR interval), RMSSD, and pNN50 (percentage of adjacent NN intervals that differ from each other by more than 50 ms).

Frequency domain analysis. Frequency domain HRV metrics complemented time domain metrics and included oscillatory components of heart rate dynamics. Spectral density was estimated using Welch's method: low frequencies (LF, sympathetic and parasympathetic activity) in the range 0.04–0.15 Hz, and high frequencies (parasympathetic activity) in the range 0.15–0.4 Hz.

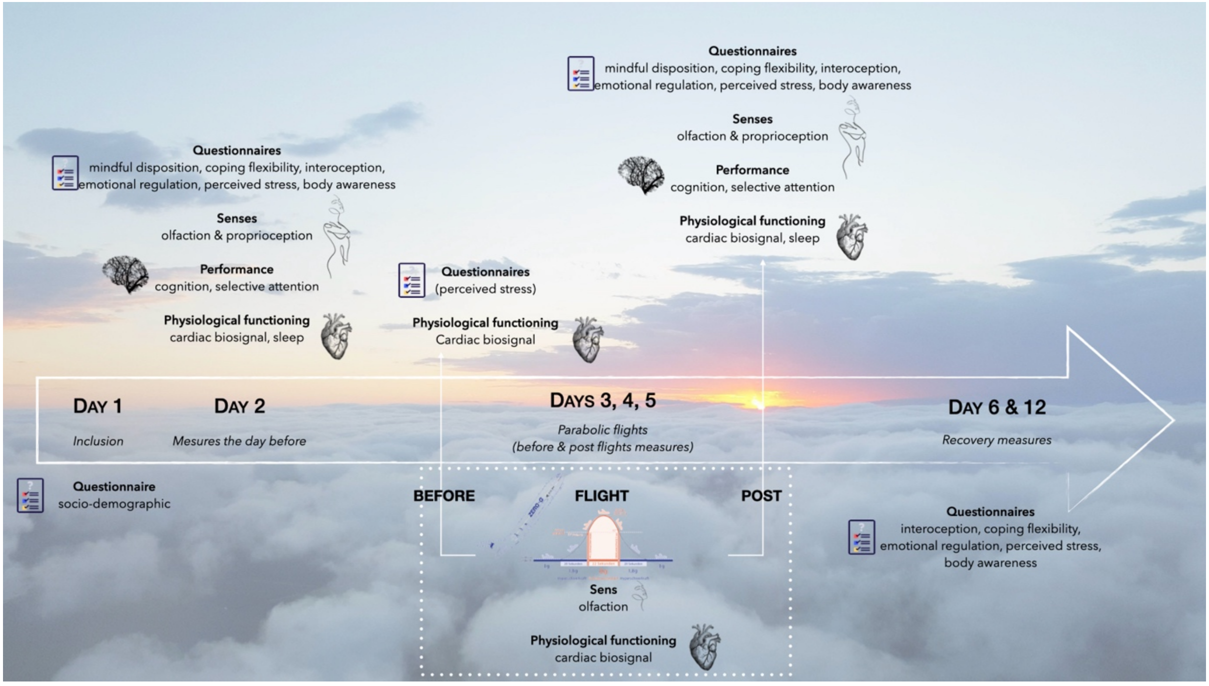
Nonlinear analysis. Nonlinear HRV metrics reflect dynamic and chaotic internal states that other metrics cannot reflect. The most representative metrics were used: the poincaré plot (i.e., graphical representation of the correlation between successive interbeat intervals), SD1 (i.e., standard deviation of instantaneous interbeat interval variability), SD2 (i.e., standard deviation of continuous, long-term RR variability), α1 (i.e., detrended fluctuation analysis self-similarity parameter that represented short-term fluctuations), α2 (i.e., detrended fluctuation analysis self-similarity parameter that represented long-term fluctuations), SampEn (i.e., sample entropy achieving the regularity and complexity of time series).

2.4. Experimental design

The microgravity experiment was run during the last week of October 2022 at Novespace (Bordeaux-Merignac International Airport, France).

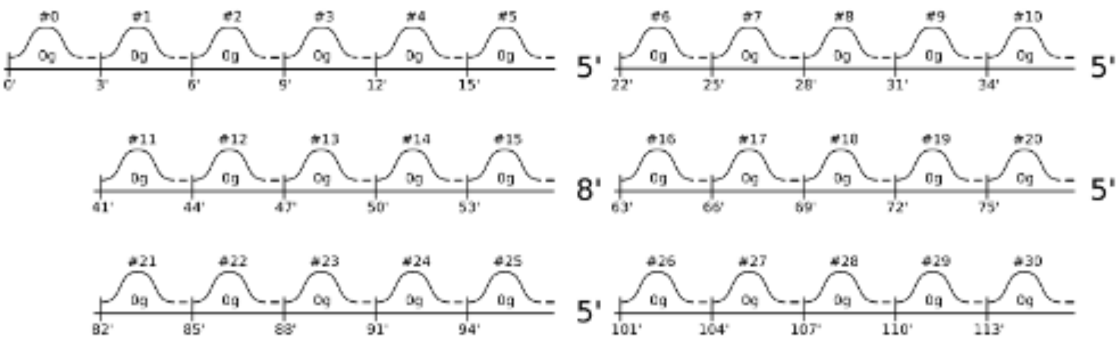
On Monday, baseline measures were performed (i.e., psychology, physiology, sensory) after verification of the inclusion criteria. The parabolic flights were organized on Tuesday, Wednesday, and Thursday (Figure 1).

Figure 1
Overview of measures collected during parabolic flight campaign



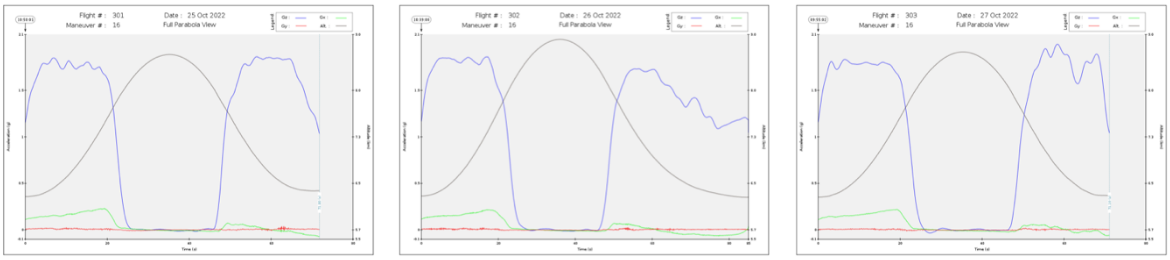
Each participant participated to one flight. They took place on board the Airbus A310 ZERO-G, a plane specially modified for microgravity. The flight runs using 30 parabolas (i.e., three to four hours). One parabola maneuver is composed of a pull-up, a microgravity phase, and a pull out (Figure 2). The duration of the microgravity phase last about 21 seconds. Data from accelerometers for each flight is shown Figure 3.

Figure 2
Parabolas' composition during a parabolic flight in microgravity



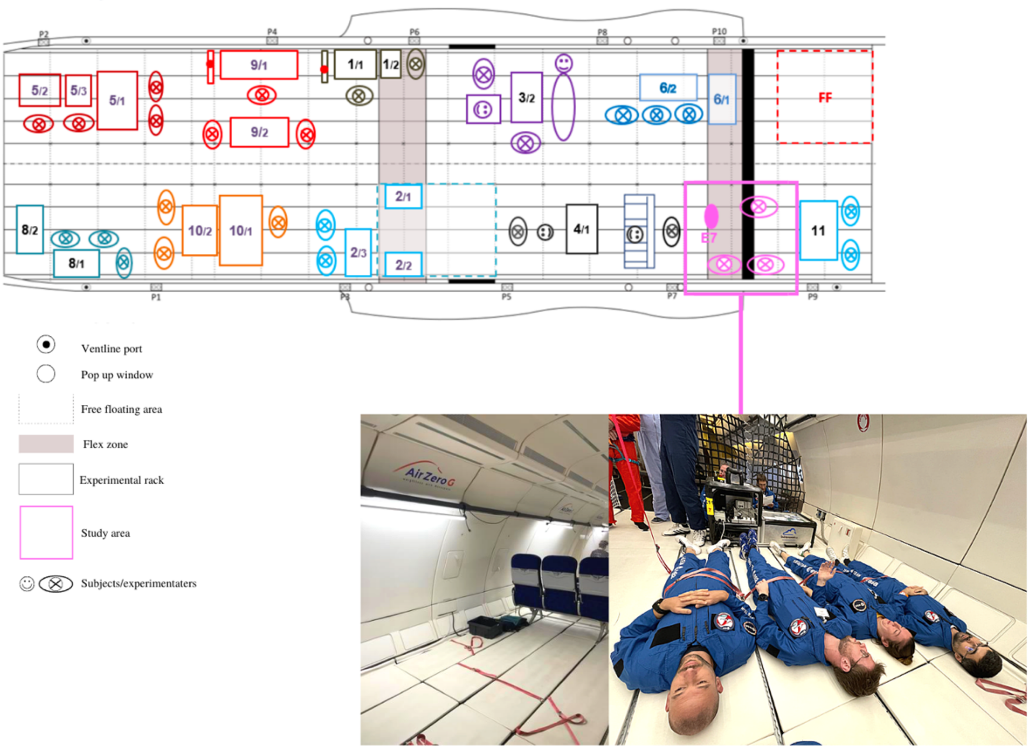
The duration of the microgravity phase last about 21 seconds. Data from accelerometers for each flight is shown Figure 3.

Figure 3
Accelerometer data of parabola 16 of the 79th parabolic flight campaign



Participants were seated in a relaxed position and were firmly and comfortably strapped to the floor in order to avoid artifacts caused by stabilization movements (Figure 4). As soon as the flight landed, postflight measurements were performed (i.e., psychology, cognitive, physiology, sensory). The day after the flight, as well as seven days later, the subjects received an e-mail link to a questionnaire to assess the recovery of the psychological state (i.e., sleep, emotions, coping flexibility, interoception, postural awareness, subjective perception of stress and senses).

Figure 4
Experimental *setting on board the Airbus A310 in microgravity*



Baseline assessments were performed the day before the flight (D−1). Preflight (pre-f) and postflight (pos-f) assessments were conducted at 7 am before boarding and just after landing. Recovery assessments took place the day after the parabolic flight (D+1), and one week after (D+7). Psychological, cognitive, and exteroceptive data were assessed at D−1 and post-f. HRV was recorded at D−1, pre-f, and post-f for the microgravity campaign. Sleep activities were recorded twice: the day before and the day after the parabolic flight (D−1 and D+1).

2.5. Statistical methods

Statistics were computed for all outcome measures. Data analyses were performed with JASP (Amsterdam, version 0.16.3), an open-source software package that is used for both classical and Bayesian analyses. Descriptive statistics were expressed as mean ± SD. The Shapiro–Wilk test was used to determine whether data were normally distributed. When the analysis was significant, effect sizes were reported. Stress adaptability was evaluated using one baseline HRV metrics, the RMSSD, linked to parasympathetic activity. Thus, the median was used to distinguish our population. In this sense, we consider the hypothesis that we have different groups based on their parasympathetic activity at rest. This statement conducts to two different profiles: the HP profile have a high parasympathetic activity and the LP profile have a low parasympathetic activity at baseline. To evaluate the difference between HP and LP profiles at baseline, ANOVA one-way analysis or Kruskal-Wallis test (i.e., depending on the normality of the distribution) were performed. Psychological, physiological, and exteroceptive states were evaluated using ANOVA repeated-measures analyses. Holm *post hoc* analyses were performed when the *p*-value was significant. Bayesian analyses were performed, by applying equivalent analyses for ANOVA repeated-measures analyses. The Bayesian Factor was calculated if no significant effect was detected. A low value provides support for the null hypothesis, and a high value indicates evidence in favor of the alternative hypothesis (Supplementary Material).

For all analyses, statistical significance was set at $p < .05$. A *p*-value between .05 and .07 was considered as evidence of a trend.

3. Results

D−1 measurements for all participants per groups are presented in Tables 2 to 4 (Supplementary Material). No difference was found between the two profiles based on the RMSSD at D−1 for health and psychological measurements, apart from coping acceptance, not distracting interoceptive sub-factor, subjective stress, and a trend for the trusting interoceptive sub-factor (Table 2); and for proprioceptive measurements, apart from the slope in opened eyes condition and the NA02 front to rear in closed eyes condition (Table 3).

Table 2

Baseline health & psychological measurements of participants

	LPa	HPa	*p*-value*
CFS			
E	4.000 ± .000	5.400 ± 1.517	.922
A	4.000 ± 1.414	5.600 ± 2.408	.433
FMI			
PR	18.875 ± 1.885	19.333 ± 1.581	.594
AC	19.375 ± 3.777	22.444 ± 2.242	**.056**
MAIA			
N	2.875 ± 1.157	3.694 ± .497	.161
ND	1.563 ± .826	2.907 ± .972	**.008**
NW	2.700 ± .701	3.156 ± .488	.137
AR	3.107 ± .735	3.286 ± 1.020	.688
EA	3.225 ± 1.000	3.244 ± .871	.966
SR	2.688 ± .989	3.222 ± .701	.214
BL	1.792 ± .975	2.667 ± 1.130	.110
T	3.333 ± 1.321	4.407 ± .703	**.077**
SPANE			
N	3.896 ± .281	4.222 ± .464	.205
P	2.354 ± .594	2.167 ± .577	.520
SQS			
SQ	6.750 ± 1.982	5.111 ± 2.315	.140
PSS			
S	63.853 ± 6.582	70.109 ± 5.608	**.051**
PAS			
PA	14.039 ± 2.947	16.126 ± 2.086	.109
NA	45.083 ± 4.846	49.407 ± 3.741	**.056**

Note. LPa = low parasympathetic functioning; HPa = high parasympathetic functioning; E = evaluation; A = adaptation; PR = presence; AC = acceptation; N = noticing; ND = not distracting; NW = not worrying; AR = attention regulation; EA = emotional awareness; SR = self-regulation; BL = body listening; T = trusting; N = negative emotions; P = positive emotions; SQ = sleep quality; S = subjective stress; PA = postural awareness; NA = need to regulate attention.

**p*-value used in the analysis of effects (ANOVA or Kruskall-Wallis test). Means and standard deviation are show for each variable.

Table 3

Baseline exteroceptive measurements of participants

	LPa	HPa	*p*-value*
ETOC			
D	15.286 ± .756	15.222 ± 1.641	.096
I	12.429 ± 1.988	13.000 ± 2.212	.592
H	82.036 ± 5.365	78.764 ± 9.676	.437
Proprioception			
OElg	626.019 ± 44.702	661.381 ± 167.313	.572
OEe	169.649 ± 53.121	167.766 ± 78.535	.955
OEs	1.469 ± .224	.302 ± 1.486	**.045**
OElfs	4.062 ± 1.438	5.124 ± 3.134	.394
OEas	11.481 ± 1.369	11.885 ± 2.928	.727
OEsv	45.633 ± 14.480	52.546 ± 28.356	.545
OElgLtR	345.825 ± 28.591	330.256 ± 71.221	.573
OErLtR	16.425 ± 2.023	16.922 ± 5.778	.821
OEvLtR	8.363 ± 2.277	8.731 ± 4.825	.847
OEsvLtR	45.633 ± 14.480	52.546 ± 28.356	.545
OEna02LtR	24.557 ± 15.922	21.379 ± 7.851	.603
OElgFtR	436.238 ± 51.864	492.111 ± 148.116	.328
OErFtR	21.512 ± 4.489	21.733 ± 6.308	.936
OEvFtR	19.926 ± 11.523	20.515 ± 13.126	.923
OEsvFtR	109.119 ± 37.087	137.814 ± 83.880	.387
OEna02FtR	20.438 ± 8.269	17.807 ± 5.343	.443
CElg	902.800 ± 258.108	824.258 ± 239.449	.525
CEe	282.588 ± 180.709	197.308 ± 100.756	.241
CEs	-.303 ± 1.535	-.399 ± 1.470	.897
CElfs	3.781 ± 1.180	4.968 ± 2.422	.228
CEas	16.272 ± 4.944	15.292 ± 4.353	.670
CEsv	125.954 ± 98.196	92.639 ± 59.180	.404
CElgLtR	466.137 ± 107.097	379.233 ± 101.603	.107
CErLtR	21.650 ± 5.842	17.544 ± 5.259	.148
CEvLtR	15.768 ± 7.693	10.305 ± 7.945	.172
CEsvLtR	137.210 ± 72.582	89.832 ± 45.181	.122
CEna02LtR	25.182 ± 3.273	24.883 ± 7.208	.916
CElgFtR	664.575 ± 225.367	644.833 ± 204.774	.852

CErFtR	26.975 ± 11.590	26.478 ± 7.362	.916
CEvFtR	26.378 ± 20.211	24.214 ± 15.553	.807
CEsvFtR	274.986 ± 223.157	253.594 ± 179.636	.830
CEna02FtR	28.621 ± 9.117	20.729 ± 6.470	**.055**

Note. LPa = low parasympathetic functioning; HPa = high parasympathetic functioning; D = detection; I = identification; H = hedonic value; OE= opened eyes; lg = logarithm; e = elliptic surface; s = slope; lfs = length ratio of the surface; as = average speed; sv = speed variance; r = range; v = variance; na02 = amplitude of postural oscillations in X and Y; LtR = left to right; FtR = front to rear; CE = closed eyes.

**p*-value used in the analysis of effects (ANOVA or Kruskall-Wallis test). Means and standard deviation are show for each variable.

Concerning physiological measurements at D−1, the groups based on the RMSSD level were different on SDNN, pNN50, LF, HF, SD1, SD2, SD ratio and $\alpha 2$ (Table 4). Previous parabolic flight experience did not highlight difference on all measures recorded. Moreover, motion sickness of participants was assessed pre-f and post-f but no significance was found between participants, whatever the RMSSD profile.

Table 4

Baseline physiological measurements of participants

	LPa	HPa	*p*-value*
Temporal domain			
Mean RR	776.582 ± 111.991	824.399 ± 122.463	.416
SDNN	40.288 ± 10.866	70.051 ± 15.654	**< .001**
RMSSD	17.472 ± 4.084	43.581 ± 11.138	**< .001**
pNN50	1.664 ± 2.132	23.191 ± 10.317	**< .001**
Frequency domain			
LF	581.156 ± 511.736	3198.754 ± 2357.656	**.001**
HF	120.895 ± 52.020	591.278 ± 288.658	**< .001**
LF/HF ratio	4.434 ± 2.372	6.785 ± 6.814	.370
Non linear domain			
SD1	12.354 ± 2.888	30.816 ± 7.876	**< .001**
SD2	55.489 ± 15.151	93.857 ± 21.446	**< .001**
SD ratio	4.465 ± .642	3.139 ± .614	**< .001**
a1	1.401 ± .129	1.272 ± .192	.130
a2	1.011 ± .144	.651 ± .232	**.003**
SampEn	1.093 ± .402	1.198 ± .324	.559

Note. LPa = low parasympathetic functioning; HPa = high parasympathetic functioning.

[*] *p*-value used in the analysis of effects (ANOVA or Kruskall-Wallis test). Means and standard deviation are show for each variable.

3.1. Psychological functioning

Coping. There is a significant effect of time on evaluation [F (2,10) = 4.888, p = .033, η^2 = .173]. *Post hoc* analyses show that the level of coping evaluation was higher at D+1(p = .056), and at D+7 (p = .056) compared to D−1.

Mindfulness disposition. There is a tendency to a significant group effect on acceptance [F (1,15) = 3.882, p = .068, η^2 = .103]. Participants with a HP profile would have a higher acceptance than those with a low LP profile.

Interoception. There are significant time effects for not distracting [F (3,45) = 2.946, p = .043, η^2 = .028] and group effect for not distracting [F (1,15) = 7.266, p = .017, η^2 =

.265], body listening [F (1,15) = 4.594, p = .049, η^2 = .217] and trusting [F (1,15) = 7.266, p = .017, η^2 = .265]. A trend to a time effect was identified for attention regulation [F (3,45) = 2.627, p = .062, η^2 = .021]. *Post hoc* analyses reveal that participants ignore or distract themself from sensations of pain or discomfort increase (p = .044) and tend to decrease their ability to sustain and control attention to their body sensations (p = .066) at D+1 compared to D−1. Also, those with a HP profile tend to ignore or distract themself from sensations of pain or discomfort, experience their body as a safe and trustworthy place, tend to actively listen the body for insight compared to those with a LP profile. For emotional awareness, the Bayesian analysis support the alternative hypothesis for the group (p = .618, BF10 = 1.822). This leads to a tendency towards a better awareness of the connection between body sensations and emotional states for participants who have a HP profile compared to those with a LP profile.

Affects. There are significant time effect [F (3,45) = 76.899, p < .001, η^2 = .722] and time*group effect [F (3,45) = 5.475, p = .003, η^2 = .051] on positive affects. There are also a significant time effect [F (3,45) = 123.705, p < .001, η^2 = .769] on negative affects without interaction. *Post hoc* analyses reveal that participants have lower positive and higher negative affects at D+1 and D+7 compared to D−1 and post-f (p < .001). Also, those with a LP profile have lower positive affects at D+1 and D+7 compared to D−1 and post-f (p < .001). Those with a HP profile have lower positive affects at D+1 and D+7 compared to D−1 and post-f (p < .001). Participants with a HP profile decrease their positive affects at D+1 and D+7 compared to those with a LP profile at D−1 and post-f (p < .001). Participants with a LP profile increase their positive affects at D+1 and D+7 compared to those with a HP profile at D−1 and post-f (p < .001).

Subjective stress. There is a significant effect of time on stress [F (2,54) = 3.716, p = .031, η^2= .121]. *Post hoc* analyses reveal that participants tend to perceive less stress at post-f (p = .063).

Postural awareness. There is a significant effect of time towards a need for attention regulation with postural awareness [F (3,45) = 3.180, p = .033, η^2 = .016]. *Post hoc* analyses show that participants tended to increase their need for attention regulation with postural awareness (p = .098) at D+1 compared to D−1.

3.2. Sleep functioning

Subjective sleep. Subjective measures revealed significant time effect on sleep quality [F (3,45) = 3.394, p = .026, η^2 = .118], repetitive thoughts before bed, [F (1,11) = 10.750, p = .007, η^2 = .088], time*group effect for physical indicators of stress [F (1,11) = 6.605, p = .026, η^2 = .180] and group effect on sleep quality [F (1,15) = 10.335, p = .006, η^2 = .145], and for physical indicators of stress [F (1,11) = 4.721, p = .053, η^2 = .125]. Trends for a time effect were found for well rested waking up [F (1,11) = 3.743, p = .079, η^2 = .118] and physical indicators of stress [F (1,11) = 3.736, p = .079, η^2 = .102]. *Post hoc* analyses show that those with a LP profile have higher physical indicators of stress before bed compared to those with a HP profile at pre-f (p = .017), at pre-f compared to D+1 (p = .043), and at pre-f compared to those with a HP profile at D+1 (p = .041). Moreover, participants have a higher sleep quality (p < .034) at D+7 compared to D−1. Overall, flyers tend to have less repetitive thoughts and physical indicators of stress before going to bed, and higher well rested waking up morning, at D+1 compared to pre-f. Also, those with a HP profile have fewer physical indicators of stress before going to bed and a lower sleep quality compared to those with a LP profile.

Sleep monitoring. The monitoring night shows a significant time effect for WASO [F (1,9) = 7.391, p = .024, η^2 = .120], sleep efficiency [F (1,9) = 6.744, p = .029, η^2 = .112], actual sleep time [F (1,9) = 10.944, p = .009, η^2 = .153] and actual wake time [F (1,9) = 7.942, p = .020, η^2 = .094]. Flyers have a higher wake-up time after falling asleep and after waking-up, a lower sleep efficiency, and sleep duration at D+1 compared to pre-f.

3.3. Exteroceptive functioning

Olfaction. A significant time effect is found for detection [F (1,14) = 6.168, p = .026, η^2 = .044]. Participants increase their ability to identify odors (p = .098) at post-f compared to D−1.

Proprioception. Significant differences were found in both opened and closed eyes conditions. Specifically, in opened eyes condition, there is a significant time*group effect for slope [F (1,15) = 6.051, p = .027, η^2 = .155]. Trends for a group effect were identified for the logarithm left to right [F (1,15) = 3.726, p = .073, η^2 = .105] and for the variance speed left to right [F (1,15) = 3.800, p = .070, η^2 = .105]. *Post hoc* analyses show that the LP profile tends to have a higher slope than the HP profile in opened eyes condition at D−1 (p = .078) whereas the HP profile tends to increase their slope at post-f compared to D−1 (p = .078). Moreover, the HP profile tend to have a lower logarithm left to right and a higher speed variance compared to the LP profile.

In closed eyes condition, there are significant time effects with an increase of the slope [F (1,15) = 15.279, p = .001, η^2 = .244], a decrease of the LFS (i.e., energetic expenditure or length ratio of the surface) [F (1,15) = 5.479, p = .033, η^2 = .061] post-f compared to D−1, and a significant group effect for the logarithm left to right [F (1,15) = .810, p = .030, η^2 = .192]. The HP profile have a lower logarithm left to right compared to the LP profile.

3.4. Physiological functioning

HRV. The following significant differences are found: there are significant time effect for RR intervals [F (2,30) = 14.251, p < .001, η^2 = .123], SDNN [F (2,30) = 5.352, p = .010, η^2 = .075], RMSSD [F (2,30) = 13.602, p < .001, η^2 = .140], pNN50 [F (2,30) = 17.156, p < .001, η^2 = .142], HF [F (2,30) = 5.673, p = .008, η^2 = .130], SD1 [F (2,30) = 13.603, p < .001, η^2 = .140], SD2 [F (2,30) = 3.941, p = .030, η^2 = .051], SD ratio [F (2,30) = 4.741, p = .016, η^2 = .115], $\alpha1$ [F (2,30) = 5.984, p = .007, η^2 = .124]; time*group effect for $\alpha2$ [F (2,30) = 5.975, p = .007, η^2 = .064], group effect for SDNN [F (1,15) = 11.541, p = .004, η^2 = .310], RMSSD [F (1,15) = 14.170, p = .002, η^2 = .338], pNN50 [F (1,15) = 16.039, p = .001, η^2 = .372], LF [F (1,15) = 6.098, p = .026, η^2 = .238], HF [F (1,15) = 8.962, p = .009, η^2 = .172], SD1 [F (1,15) = 14.170, p = .002, η^2 = .338], SD2 [F (1,15) = 12.087, p = .003, η^2 = .337], SD ratio [F (1,15) = 11.915, p = .004, η^2 = .221], $\alpha2$ [F (1,15) = 6.482, p = .022, η^2 = .233]. Trends are identified for a time effect for SampEn [F (2,30) = 3.063, p = .062, η^2 = .077] and for a time*group effect for HF [F (2,30) = 2.855, p = .073, η^2 = .066].

Post hoc analyses reveal that participants have higher RR intervals, RMSSD, pNN50, SD1, SD2 at post-f compared to D−1 and pre-f (p < .001), a higher SDNN at post-f compared to D−1 (p = .029) and pre-f (p = .015), a higher HF at post-f compared to D−1 (p = .016) and pre-f (p = .017), a higher SD ratio at post-f compared to D−1 and pre-f (p = .033), a higher $\alpha1$ at post-f compared to D−1 (p = .012) and pre-f (p = .016). Those with a HP profile increase their HF at post-f compared to D−1 (p = .010), pre-f (p = .014) and compared to those with a LP profile activation at D−1 (p = .001), pre-f (p = .002). They have a lower $\alpha 2$ at D−1compared to those with a LP profile at pre-f (p = .047). At post-f, those with a HP profile increase their HF compared to those with a LP profile (p = .006). At D−1, flyers with a HP profile have a lower $\alpha 2$ compared to those with a LP profile (p = .015). Also, the HP profile have a higher SDNN, RMSSD, pNN50, LF, SD1, SD2 and a lower $\alpha 2$ compared to those with a LP profile. Participants tend to increase their SampEn at post-f compared to D−1 (p = .063).

Table 5 present a summary of these psychological, physiological, and sensory differences following the experiment.

Table 5

Summary of the impact of parabolic flight on body functioning

	Baseline		Pre-f		Post-f		D+1		D+7		*p*-value*
	LPa	HPa	LPa	HPa	LPa	HPa	LPa	HPa	LPa	HPa	
CFS											
E[a]	4.000 ± .000	5.400 ± 1.517					7.500 ± .707	6.000 ± 2.449	7.000 ± 1.414	6.200 ± 2.683	.033
FMI											
A[c]	19.375 ± 3.777	22.444 ± 2.242					20.000 ± 3.071	21.889 ± 2.028	19.625 ± 3.021	22.000 ± 2.963	.068
MAIA											
ND[a,c]	1.563 ± .826	2.907 ± .972			1.792 ± .589	2.519 ± .891	1.458 ± .452	2.204 ± .964	1.604 ± .684	2.519 ± .797	.017
AR[a]	3.107 ± .735	3.286 ± 1.020			2.586 ± .924	3.270 ± .679	2.500 ± 1.198	3.175 ± .874	2.714 ± 1.091	2.714 ± 3.381	.062
BL[c]	1.792 ± .975	2.667 ± 1.130			1.708 ± 1.046	2.741 ± 1.038	1.958 ± 1.046	3.037 ± 1.230	2.000 ± 1.182	3.000 ± 1.236	.049
T[c]	3.333 ± 1.321	4.407 ± .703			3.125 ± 1.447	4.370 ± .696	3.417 ± 1.456	4.407 ± .596	3.458 ± 1.553	4.556 ± .726	.017
SPANE											
N[a]	3.896 ± .281	4.222 ± .464			4.062 ± .333	4.389 ± .449	2.625 ± .469	1.963 ± .790	2.625 ± .469	1.963 ± .790	.003
P[a,c]	2.354 ± .594	2.167 ± 577			2.417 ± .398	2.056 ± .507	4.063 ± .377	3.833 ± .449	4.063 ± .377	3.833 ± .449	< .001
SQS											
SQ[a,c]	6.750 ± 1.982	5.111 ± 2.315			7.250 ± .707	5.556 ± 1.424	7.625 ± 1.598	6.667 ± 1.658	8.250 ± 1.282	6.889 ± 1.900	.006
PSS											
S[a]	30.000 ± 3.117	28.778 ± 3.032			30.625 ± 2.973	28.556 ± 3.087	30.875 ± 3.482	28.000 ± 3.464	30.875 ± 5.194	28.333 ± 3.808	.031
PAS											
PA[a]	22.750 ± 5.898	25.444 ± 7.091			22.500 ± 7.764	26.444 ± 6.327	24.250 ± 7.166	27.778 ± 6.515	23.500 ± 7.426	28.222 ± 6.220	.033
PS											

SQ[a,c]	6.750 ± 1.982	5.111 ± 2.315	7.250 ± .707	5.556 ± 1.424			7.625 ± 1.598	6.667 ± 1.658	8.250 ± 1.282	6.889 ± 1.900	.026
RT[a]			2.597 ± 2.538	1.221 ± 2.155			.986 ± 1.868	.498 ± 1.058			.007
PIS[a,b,c]			2.735 ± 2.663	.130 ± .214			.245 ± .241	.482 ± 1.064			.026
WRw[a]			5.133 ± 1.156	5.041 ± 1.728			5.554 ± 2.089	6.726 ± .685			.079
ETOC											
D[a]	12.429 ± 1.988	13.000 ± 2.121			13.714 ± 1.976	13.333 ± 1.871					.026
Actimeter											
WASO[a]			31.167 ± 16.241	46.400 ± 10.621			46.667 ± 29.412	61.000 ± 21.131			.024
SE[a]			89.361 ± 4.828	85.021 ± 7.104			85.210 ± 6.708	79.906 ± 8.080			.029
AST[a]			91.996 ± 4.389	88.192 ± 3.482			86.437 ± 6.798	85.670 ± 4.357			.009
AWT[a]			8.004 ± 4.389	11.808 ± 3.483			12.082 ± 7.738	14.330 ± 4.357			.020
Proprioception											
OEs[b]	1.469 ± .224	.302 ± 1.486			1.129 ± 1.074	1.548 ± .019					.027
OElLtR[c]	345.825 ± 28.591	330.256 ± 71.221			374.425 ± 95.218	300.233 ± 59.135					.073
OEsvLtR[c]	70.013 ± 13.607	63.629 ± 32.025			89.666 ± 47.646	54.894 ± 20.500					.070
CEs[a]	-.303 ± 1.535	-.399 ± 1.470			.910 ± 1.155	1.199 ± 1.011					.001
CElfs[a]	3.781 ± 1.180	4.968 ± 2.422			3.480 ± 1.822	3.510 ± 1.390					.033
CElLtR[c]	466.137 ± 107.097	379.233 ± 101.603			455.337 ± 120.130	358.233 ± 66.972					.030
HRV											
Mean RR[a]	776.582 ± 111.991	824.399 ± 122.463	775.481 ± 103.618	805.321 ± 143.557	851.679 ± 121.769	945.870 ± 181.081					< .001
SDNN[a,c]	40.288 ± 10.866	70.051 ± 15.654	35.987 ± 14.426	69.040 ± 41.633	52.720 ± 13.221	89.112 ± 31.862					.004
RMSSD[a,c]	17.472 ± 4.084	43.581 ± 11.138	19.354 ± 3.420	42.652 ± 24.936	32.489 ± 13.123	67.313 ± 31.217					.002
pNN50[a,c]	1.664 ± 2.132	23.191 ± 10.317	1.716 ± 1.318	21.209 ± 19.341	12.603 ± 10.853	42.034 ± 22.861					.001
LF[a,c]	581.156 ± 511.736	3198.754 ± 2357.656	621.271 ± 505.540	3283.969 ± 3573.229	1134.826 ± 914.672	4188.095 ± 4354.523					.026

HF[a,b,c]	120.895 ± 52.020	591.278 ± 288.658	162.992 ± 81.660	655.102 ± 571.075	369.769 ± 349.655	1969.084 ± 1931.997	.009
SD1[a,c]	12.354 ± 2.888	30.816 ± 7.876	13.685 ± 2.418	30.159 ± 17.631	22.973 ± 9.279	47.597 ± 22.073	.002
SD2[a,c]	55.489 ± 15.151	93.857 ± 21.446	56.192 ± 11.782	99.083 ± 49.255	70.567 ± 17.609	116.082 ± 40.736	.003
SD ratio[a,c]	4.465 ± .642	3.139 ± .614	4.174 ± .859	3.474 ± .590	3.479 ± 1.303	2.733 ± .851	.004
a1[a]	1.401 ± .129	1.272 ± .192	1.349 ± .209	1.287 ± .202	1.224 ± .297	1.053 ± .351	.007
a2[b,c]	1.011 ± .144	.651 ± .232	.963 ± .180	.767 ± .221	.881 ± .112	.794 ± .242	.022
SampEn[a,c]	1.093 ± .402	1.198 ± .324	1.336 ± .444	1.121 ± .249	1.317 ± .323	1.447 ± .343	.062

Note. LPa = low parasympathetic with less unpredictability and flexibility cardiac biosignal; HPa = high parasympathetic with greater unpredictability and flexibility cardiac biosignal; E = evaluation; A = acceptation; ND = not distracting; AR = attention regulation; BL = body listening; T = trusting; N = negative emotions; P = positive emotions; PS = perceived sleep; S = subjective stress; PA = postural awareness; SQ = sleep quality; WASO = wake actual sleep onset; SE = sleep efficiency; AST = actual sleep time; AWT = actual wake time; D = detection; OEs = slope in opened eyes condition; OElLtR = logarithm left to right in opened eyes condition; OEsvLtR = speed variance left to right in opened eyes condition; CEs = slope in closed eyes condition; CElfs = length ratio of the surface in closed eyes condition; CElLtR = logarithm left to right in closed eyes condition.

[*] *p*-value used in the analysis of effects. Means and standard deviations are shown for each variable. All variables were recorded at four times, appart from proprioception where baseline and recovery were collected. Only significant interactions were reported ($p < .05$).

[a] Significant time effect.

[b] Significant time*group effect.

[c] Significant group effect.

4. Discussion

The advent of space tourism raises health issues concerning the individuals who will compose the crews. Today, the only transfers for an astronaut are approximately every six months from Earth to the ISS, and astronauts stay for a specific time in the ISS environment. Space tourism will involve journeys of at least a few hours and stays of varying lengths at space bases. Inter-base trips will also be considered. For these individuals, selection will be based not on physical, intellectual, and motivational abilities, but on financial criteria. Tomorrow, we will have to prepare a candidate who does not meet the astronauts' aptitude criteria. This new paradigm raises the question of risk after a single trip, after repeated trips and during stays on base. With the construction of the future Gateway lunar base, and in the more distant future of the next colonies to Mars, travel from one point to another will be much more frequent. In this context, a risk assessment must be carried out for short- and medium-term « tourist missions ». If this future of space tourism is still to be built, the first challenge will involve journeys. These voyages will be characterized by repeated changes in gravity using parabolic flight paradigm.

Studying the impact of these repeated gravity changes on the psychophysiological and exteroceptive responses of these tourists is a key factor in ensuring the success of these missions. Knowledge of these impacts will enable countermeasures to be considered. Therefore, our study has two main objectives: (1) to investigate the impact of repeated changes in gravity, including microgravity, on psychological, physiological, cognitive, and sensory conditions; and (2) to assess recovery from a parabolic flight experience one week later. A third objective was to evaluate whether a high parasympathetic level at baseline was a biomarker of a better response to the challenge of the parabolic flight challenge. The main findings of this study are as follows: (1) a significant decrease in the subjects' psychophysiological state of functioning the following day and up to one-week post-f; (2) different profiles based on their parasympathetic activity at baseline, a HP profile having a better interoceptive sensitivity and more aware of the present moment while they perceived more subjective stress and were more impacted on affects at recovery, adaptative proprioception; and higher HIRV compared to the LP profile and (3) flying experience ranging from first-time flyers (i.e., first flight), intermediate flyers (i.e., less than 10 flights) to expert flyers (i.e., more than 30 flights) had no impact on our results. This last result is important, as it highlights that regardless of the number of hours flown, it induces the same changes in psychophysiological, and sensory responses.

The quality of interception does not depend on the subjects' flying experience; it could constitute an endophenotype characterizing the subjects' response modality that could be accessible to simple countermeasures.

4.1. Impact of repeated gravity changes on human factors

Our study sheds light on the impact of repeated gravity changes, including microgravity, on psychophysiological and exteroceptive responses. Psychological measures indicate that repeated gravity changes induce positive outcomes at post-f, except for postural stability. Those with a high level of parasympathetic functioning (HP profile) tend to have a better acceptance (i.e., non-reactivity to inner experience) of how things are in the present moment and without judgment than LP profile. Moreover, they have a better interoceptive awareness. Individuals under the HP profile tend to ignore or distract themself from sensations of pain or discomfort, experience their body as a safe and trustworthy place, tend to actively listen the body for insight and to have a higher connection between body sensations and emotional states compared to the LP profile. Therefore, the HP profile would be more attentive and aware to the information received from the inner body and more able to live in the present moment. DeHart [77] highlighted that individuals must immediately accept the reality of the environment and react to their surroundings. Since the parabolic flight experience has no impact on psychophysiological and proprioceptive response, the regular flights to which space tourists will be subjected will not be sufficient to induce long-term adaptation. While brain neuroplasticity enables the human body to efficiently adapt to changes in the environment in a few minutes, the quality of this adaptation in the longer term will differ depending on the resources and reserves that the individual is able to mobilize, as well as their physical and mental preparation [77].

About sleep, overall, those with a HP profile have fewer physical indicators of a state of stress before sleep than the LP profile, but this is also significant at pre-f. Moreover, flyers tend to perceive less subjective stress post-f. This statement is corroborated by the HRV measures. They have higher RR intervals, SDNN, RMSSD, pNN50, HF, SD1, SD2, SD ratio, $\alpha1$ at post-f compared to D−1 and pre-f. Also, participants tend to increase their SampEn at post-f compared to D−1. The flight leads to a decline in psychological and physiological stress. They have a higher HRV, with higher unpredictability and flexibility of their signal. Studies has been linked these findings with a greater adaptability and a higher health [45, 78, 79]. Thus, flyers have an increase in the functioning of the sympathetic and parasympathetic components of the autonomic nervous system, especially the HP profile. This one remains with a higher parasympathetic functioning toward the LP profile.

Proprioception was deeply impacted during our experiment. Effects were observed in both closed and open eyes conditions for slope, energy, logarithm in the left to right plan. More specifically, under opened-eye conditions, the LP profile showed a trend towards a higher left/right logarithm, as well as a higher slope and a lower left/right velocity variance than the HP profile, possibly reflecting a reduced symmetry or postural stability between the left and right sides of the body, and thus an altered postural balance. Moreover, at post-f, flyers showed an increase in slope (i.e., probably linked to tilt or displacement of the center of pressure) in both opened-eye and closed-eye conditions compared to pre-f, as well as a decrease in energy but only in closed-eye conditions. This result may indicate a greater alteration in postural balance in the absence of visual references. The HP profile, meanwhile, appears to be the most affected, with a tendency for the slope to increase at post-f compared to pre-f. Human beings are familiar with utilizing dependable visual, vestibular, and somatosensory cues to govern intricate balance processes. The central nervous system receives the incoming information from proprioceptive signals and tactile mechanoreceptors to perceive the bodily position and movement in space. These signals are then integrated with visual and vestibular inputs [80, 81] and contribute to postural stability [82]. A study in the NEMO habitat analog found that crew members had not recovered their pre-mission sensorimotor performance after several weeks [83]. Postural stability and control involve high-level cognitive functions, such as attention to bodily cues that provide information about the body's orientation in space [84]. In this context, earlier work [85] demonstrates that the slope of the line that connects the local CoP to the mean location index provides clinical information about potential pelvic torsion; at the same time, factors associated with postural instability have been shown to be associated with reduced sensation [86]. At the exteroceptive plan, flyers have a better identification of odors at post-f compared to baseline. Stress is known to increase the perception of odors. A study shows a link between cortisol and odors identification [87].

Overall, the parabolic flights induce a decrease in psychological and physiological stress but impaired postural balance. The HP profile may be protective, notably through a better interoceptive sensitivity and a higher parasympathetic functioning, compared to the LP profile, providing a more adaptative and flexible response behavior.

4.2. Implications of physiological profiles at baseline

At D−1, the HP profile have a better interoceptive sensitive than the LP profile, highlighted by a higher attitude of acceptance in the present moment, a lower ignorance or distraction from sensations of pain or discomfort, and a trend to a better trusting in their body sensations. This profile has been associated with emotional balance, well-being, less pathological disorders [43, 88–92], and thus better health outcomes and self-awareness. Nevertheless, they perceived high subjective stress. This apparently contradictory response is not entirely irrelevant. It is important to note that parasympathetic activation does not necessarily mean less perceived stress. In some cases, an active parasympathetic response may be a compensatory reaction to high levels of perceived stress, aimed at reducing the negative effects of stress on the body. Thus, although the HP profile may show better physiological stress regulation, as well as a higher coping acceptance, they may still perceive a subjective stress as they recognize it. In addition, there are complex interactions between the parasympathetic and sympathetic branches of the autonomic nervous system. The HP profile function in response to a challenging situation and are in an acceptance situation of what they experience. Thus, this profile does not necessarily reflect complete inhibition of the sympathetic response. The HP profile may therefore have a finer modulation of autonomic regulation, which could enable them to perceive their subjective stress more clearly while maintaining a certain physiological stability. This result is linked to the physiological activation of the ANS. The multimodal integration across interoceptive processing is well established in the literature.

Some HRV indicators highlighted a strong parasympathetic tone and effective autonomic regulation of the HP profile towards the LP profile (i.e., a higher SDNN, pNN50, LF, HF, SD1, SD2, SD ratio). This indicates that individuals with an HP profile have a better capacity for autonomic regulation, which can be beneficial in terms of stress resilience, recovery, and physiological balance. Nevertheless, the HP profile show a lower SD ratio and $\alpha 2$ index. The SD ratio is associated with the randomness of the HRV signal. In the context of HRV, this might mean that the heart rate fluctuations are less structured or show reduced fractal-like behavior over time. This pattern could indicate that the HP profile has a regulatory strategy that prioritizes rapid adaptability and responsiveness, possibly due to their strong parasympathetic influence. Thus, the HP profile might be indicative of a finely tuned regulatory response that does not require as much broad-scale modulation compared to the LP profile. All together, these results show that stress acts bidirectionally on the brain-body axis [93]. Both psychological and physiological responses highlight the HP profile have a specific regulatory pattern that contributes to their resilience and adaptability in the face of stressors.

Moreover, the HP profile has a lower slope with eyes open and a lower NA02 with eyes closed than the LP profile. This result may reflect a better ability of the postural system to maintain stability and reduce excessive body oscillations in response to perturbations before a challenge. These results could be linked to better parasympathetic modulation, promoting finer control and greater stability during balance tasks on the stabilometric platform. The better interoceptive and proprioceptive abilities for the HP subjects suggest that they could have a better brain-body connection. The connections between the brain and the body are bidirectional [94]. Afferent pathways integrate internal information and send signals to the central nervous system (i.e., the internal regulatory system responsible for interpreting and integrating signals concerning the body's internal state, essential for survival) for evaluation. Efferent pathways refer to communication between the brain and physiological systems. Consequently, the interoceptive network mobilizes numerous brain regions, including the insular cortex, cingulate cortex, inferior frontal gyrus and sensorimotor cortex. These structures in turn project onto other structures involved in psychological, cognitive, physiological, and sensory regulation processes. Signals are thus encoded multimodally via interoceptive pathways, but also exteroceptive via peripheral receptors (i.e., visual, vestibular, somatosensory). Craig [88] show that vagal and spinal afferents may represent parasympathetic and sympathetic signal activities. These two branches of the ANS may inhibit each other into the interoceptive regions of the brain.

Thus, these results suggest a baseline endophenotype response between two profiles characterized by their level of parasympathetic functioning towards a better or less adaptative, their self-awareness though interoceptive sensitivity profile and their standing postural regulation.

4.3. Need to prepare postflight experience by integrate the recovery to the space experience

The recovery period seems to be the one for which the impact of repeated changes in gravity, including microgravity, is major and persistent. Many individuals did not recover, or even deteriorated further. Sleep and emotions seem to be the most impaired components.

Subjects show an increase in coping flexibility at D+1 and D+7, reflected in the abandonment of strategies deemed ineffective for adaptation via a process of understanding one's environment, monitoring and evaluating results, and abandoning the coping strategy when results are unfavorable. The lack of significance for the « adaptation » dimension reflects the absence of implementation of an alternative strategy. Kato [95] defines coping flexibility as « the ability to discontinue an ineffective coping strategy and produce and implement an alternative coping strategy ». Coping flexibility makes it possible to respond to environmental demand in order to produce more adaptive outcomes [96]. Abandoning an ineffective strategy has been linked to protection against repeated failure, and thus orientation towards a depressive or potentially health-damaging state [97 99]. Similarly, Kato et al. [100] showed that the quit strategy was correlated with low psychological stress. Moreover, flyers' tendency to ignore or distract themselves from sensations of pain or discomfort increases, and their ability to maintain and control their attention on their bodily sensations tends to decrease in post-f. They recovered at D+7, although the values have not yet returned to baseline.

In terms of affect, subjects experienced a drop in positive affect and an increase in negative affect at D+1 and D+7 compared to baseline and post-f. This result means that the experience of repeated changes in gravity induces very strong positive affects, with a return to reality that can be complex to cope with following the extraordinary experience. A week before the end of the flights, the emotional impact is still present. The only difference in positive affect is linked to the parasympathetic functioning of the flyers. Regardless of profile, both had a decrease in positive affect. However, those with an HP profile showed the greatest decrease compared to those with an LP profile. Schneider et al. [38] demonstrated mood changes during a parabolic flight, reflecting an increase in environmental demand. Sleep monitoring revealed that flyers had higher wakefulness, reduced sleep efficiency and difficulty waking up at night and on morning D+1. However, they felt they had a better night's sleep than the pre-f night. Nevertheless, the HP profile had poorer sleep quality than the LP profile. These results are in line with the better interoceptive and cardiac biosignal functioning highlighted earlier. It's worth noting that individuals report less repetitive thoughts and physical indicators of stress at D+1, and better sleep quality at D+7. This result gives rise to two facts: the first relates to the intense preparation inherent in parabolic flights, which leads to greater fatigue, and the second to the need for recovery spread over a period of up to a week. Moreover, flyers tend to have a need to regulate attention to the body higher at D+1. This result may be related to the impact of parabolic flight on postural control and may suggest the need to recover countermeasures.

4.4. Perspectives towards a new space area

In summary, our results demonstrate no major deterioration in psychophysiological functioning due to repeated changes in gravity, including microgravity. In all the flyers, the post-f phase undermines the interoceptive components, with a willingness to ignore internal information. Although not significant, we can see from the curves that at D+7 the values have not returned to those measured at D-1. Even so, they are determined to regulate their attention to the body via postural awareness. It's as if they were looking for a way to manage their psychic state and thus find a coping mechanism. They show that subjects with high parasympathetic functioning are those for whom the after-experience is the most difficult to cope with, even though they have a higher level of interoceptive awareness than those with lower parasympathetic functioning. They also have poorer sleep quality. This profile, combined with high parasympathetic functioning, reflects a greater awareness of the environment. They are aware of what's going on around them, regardless of whether the information received is positive or negative. This seems to indicate a better adaptation. In terms of cardiac bio-signals, the results were in accordance with the challenge, with an increase in HRV at the end of the flight, but also via a coactivation of SNS and SNP, particularly in those with a HP profile compared with those with a LP profile.

These results reflect the need to take care of the after-experience of parabolic flights in the context of space tourism, especially those with high parasympathetic activation. Thus, every training session should include preparation (i.e., coaching) for the aftermath, to avoid any psychic difficulties that might result. The next flights will have to prepare people who, on the face of it, would never go into space one day, by following a rigorous training program. The latter will have to follow the latest advances in personalized medicine, in order to offer a program tailored as closely as possible to the needs of each individual. This will be the challenge of the next few years. It has become urgent to establish a framework to regulate space tourism from the point of view of health behaviors.

Even our results do not suggest that repeated changes in gravity will constitute a major health risk, they underline that the experience of parabolic flight induces psychophysiological and proprioceptive changes that can have consequences in everyday life. These changes are still present after one week, which means that post-f training programs need to include modules designed primarily to strengthen cognitive and emotional resources, and even to introduce systematic monitoring of crews during the post-f weeks. Training programs for future crews in space tourism need to be developed. A blank canvas can be used to build comprehensive modules for physical preparation, without forgetting the psychological and cognitive dimensions. Antuñano et al. [1] have highlighted several medical conditions for space tourists, including deformities of the musculoskeletal system, illnesses, injuries, infections, impaired senses, tumors, treatments, or any history of psychological and psychiatric disorders, neurodegeneration, addictions, but also everything to do with personal hygiene, sleep quality and physical fitness, which must not compromise flight safety. Pre-f medical screening is therefore pre-determined and requires the utmost attention. These courses may include a theoretical framework, practical modules for learning soft skills essential to crew safety (e.g., communication, cohesion, teamwork) and techniques for managing emotional and cognitive stress levels (e.g., cardiac coherence, meditation, games), training to increase the body's resistance in centrifuges, hypobaric chambers, parabolic flight, drop towers and any other environment that may be analogous to orbital missions. Finally, a post-f preparation module will be essential to limit any psychophysiological disorders that may result.

Space tourists are in for a unique experience few human beings have ever had. Observing one's « earthly » home beyond the boundaries of the atmosphere is no mean feat. Astronauts have long reported experiencing emotions so strong that they could lead to sensations beyond the real, mystical. Some astronauts have experienced profound psychic upheavals on their return to Earth. This needs to be assessed in advance, in order to target individuals at risk.

Differential vision makes it possible to target countermeasures tailored to individual profiles, paving the way for personalized preparation for space travel. In addition, these results contribute to our understanding of the real human challenge of adapting to the constraints imposed by space travel. Who among us could have imagined 100 years ago that the most common of mortals could find himself in orbit? Looking up at the stars and wishing to reach them will no longer be a dream, but a possibility. We are pushing aside the boundaries of reality, turning the most universal of dreams into reality. Further research is therefore warranted to better understand typical stress environments, to highlight their impact on the human body and behavior, and to understand how humans adapt to them against all odds. It is essential not only to better manage the risks of disorders prior to departure on deep space missions, but also to propose relevant and effective countermeasures to significantly reduce.

5. Limitations

This study has several methodological shortcomings that are inherent to the ecological environment. First, the paradigm in which we operate is space tourism, in which individuals will undergo repeated changes of gravity. These changes will not be as rhythmic as in a parabolic flight campaign, with a limited flight time of approximately 3 hours. The reality of the flight plan will therefore be different. Nevertheless, there is no paradigm closer to what space experiences will be like for tourists today. Second, the small sample size, and an imbalance between male and female, and right- and left-handed subjects. Studying such a population is complex, both in terms of time constraints, and access to infrastructure and personnel (operational constraints, attendance). Both the scientific team and participants must be flexible to run such an experiment. Third, our results are not reproducible beyond the specific experimental conditions and cannot be generalized. Fourth, psychological and interoceptive data (collected through questionnaires) are subjective measures. Intelligent sensors would provide more objective measures of subjects' adaptation to extreme environments. Moreover, while the PolarH10 belt is currently the best tool to accurately record RR intervals with the minimum of artifacts given our environmental constraints, the device cannot replace an ECG.

6. Conclusion

The present study is one of the first to describe the impact of repeated gravity changes, including microgravity on psychophysiological, cognitive, and sensorial responses. These results raise the question of the risks that may be induced by space tourism. They highlight two major findings: (1) the health of future space tourists does not appear to be at risk, as long as the individuals involved are healthy (e.g., with no pathologies that would make them unfit for flight); and (2) the need to take care of crews over several days or even weeks and/or include a module to prepare them for the post-f period and the return to life on Earth. This study is the first to explore the psychological responses to one-week recovery from parabolic flight. The importance of preparation not only allows us to reflect on the preparation of tomorrow's regular trips, with a population likely to be relatively heterogeneous, but also to target countermeasures adapted to individual profiles, opening the way to personalized preparation for space travel. Beyond this, these results contribute to our knowledge of the real human challenge of confronting the constraints of space travel.

7. References

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8. Supplementary Material

Coping. None of the adaptation dimension for time (p = .348, BF_{10} = .438), time*group (p = .168, BF_{10} = .320) and group (p = .832, BF_{10} = .708) reach significance. For evaluation dimension, time*group (p = .168, BF_{10} = .635) and group (p = .851, BF_{10} = .574) did not change.

Mindfulness disposition. No significant change were found for presence dimension at time (p = .381, BF_{10} = .324), time*group (p = .885, BF_{10} = .163), group (p = .840, BF_{10} = .488); and for acceptance dimension at time (p = .965, BF_{10} = .101), time*group (p = .523, BF_{10} = .147).

Interoception. None of the differences in the following interoceptive measures reached significance: noticing at time (p = .668, BF_{10} = .145), time*group (p = .381, BF_{10} = .128), group (p = .194, BF_{10} = .956); not distracting at time*group (p = .129, BF_{10} = 1.000); not worrying at time (p = .637, BF_{10} = .130), time*group (p = .274, BF_{10} = .073), group (p = .461, BF_{10} = .558); attention regulation at time*group (p = .186, BF_{10} = .855), group (p = .213, BF_{10} = .934); emotional awareness at time (p = .528, BF_{10} = .425), time*group (p = .721, BF_{10} = .244); self-regulation at time (p = .579, BF_{10} = .115), time*group (p = .767, BF_{10} = .149), group (p = .088, BF_{10} = 1.000) ; body listening at time (p = .230, BF_{10} = .242), time*group (p = .951, BF_{10} = .349), and trusting at time (p = .257, BF_{10} = .188), time*group (p = .797, BF_{10} = .313).

Motion sickness. Neither of the following measures at each timepoint: nauseas for time (p = .464, BF_{10} = .460), time*group (p = .464, BF_{10} = .196), group (p = .908, BF_{10} = .460); dizziness of eyes for time (p = .610, BF_{10} = .382), time*group (p = .610, BF_{10} = .167), group (p = .485, BF_{10} = .456); vertigo for time (p = .694, BF_{10} = .359), time*group (p = .694, BF_{10} = .150), group (p = .728, BF_{10} = .398) changed significantly.

Emotion. Positive affect did not change significantly for group (p = .306, BF_{10} < .000), and negative affect for time*group (p = .907, BF_{10} = .865) and group (p = .166, BF_{10} < .000).

Sleep. None of the following subjective sleep measures reach significance: sleep quality at time*group (p = .911, BF_{10} = 1.000); well rested waking up morning at time*group (p = .270, BF_{10} = .543) and group (p = .410, BF_{10} = .266); good quality of sleep at time (p = .096, BF_{10} = 1.000), time*group (p = .405, BF_{10} = .590) and group (p = .490, BF_{10} = .432); vivid dreams at time (p = .613, BF_{10} = .344), time*group (p = .708, BF_{10} = .416) and group (p = .136, BF_{10} = 1.000); frequently woke up at time (p = .131, BF_{10} = 1.000), time*group (p = .597, BF_{10} = .699) and group (p = .185, BF_{10} = 489); repetitive thoughts before bed at time*group (p = .238, BF_{10} = .741) and group (p = .384, BF_{10} = 143).

None of the following physiologic sleep measures reach significance: WASO at time*group (p = .937, BF_{10} = .875) and group (p = .227, BF_{10} = 221); sleep efficiency at time*group (p = .793, BF_{10} = .885) and group (p = .217, BF_{10} = 293); wake period during night at time (p = .084, BF_{10} = 1.000), time*group (p = .834, BF_{10} = .759) and group (p = .217, BF_{10} = 499); actual sleep time at time*group (p = .245, BF_{10} = .693) and group (p = .432, BF_{10} = .089); actual wake time at time*group (p = .523, BF_{10} = .778) and group (p = .345, BF_{10} = .192).

Subjective stress. Perception of stress did not change significantly at each time point: time (p = .991, BF_{10} = .083), time*group (p = .757, BF_{10} = .081) and group (p = .148, BF_{10} = .981).

Postural awareness. None of the ease/familiarity with postural awareness at time (p = .317, BF_{10} = .514), time*group (p = .688, BF_{10} = .275), group (p = .185, BF_{10} = .833) or need for attention regulation with postural awareness at time*group (p = .615, BF_{10} = .798), group (p = .259, BF_{10} = .367) indices changed significantly.

Olfaction. No significant change was found for detection at time (p = .717, BF_{10} = .341), time*group (p = .415, BF_{10} = .224), group (p = .712, BF_{10} = .620); identification at time*group (p = .166, BF_{10} = .607), group (p = .922, BF_{10} = .323), and hedonic value at time (p = .450, BF_{10} = .424), time*group (p = .710, BF_{10} = .343), group (p = .366, BF_{10} = .775).

Proprioception. In the opened eyes condition, none of the following differences were significant: logarithm at time (p = .785, BF_{10} = .344), time*group (p = .182, BF_{10} = .147) and group (p = .594, BF_{10} = .436); ellipse at time (p = .117, BF_{10} = 1.000), time*group (p = .529, BF_{10} = .485) and group (p = .559, BF_{10} = .403); slope at time (p = .180, BF_{10} = .306), and group (p = .259, BF_{10} = .187); LFS at time (p = .152, BF_{10} = .994), time*group (p = .313, BF_{10} = .433) and group (p = .658, BF_{10} = .429); average speed at time (p = .910, BF_{10} = .323), time*group (p = .177, BF_{10} = .161) and group (p = .467, BF_{10} = .473); speed variance at time (p = .716, BF_{10} = .333), time*group (p = .124, BF_{10} = .162) and group (p = .466, BF_{10} = .468); logarithm left to right at time (p = .976, BF_{10} = .324), and time*group (p = .228, BF_{10} = .339); range left to right at time (p = .449, BF_{10} = .421), time*group (p = .135, BF_{10} = .224) and group (p = .316, BF_{10} = .557); variance left to right at time (p = .086, BF_{10} = 1.000), time*group (p = .107, BF_{10} = .709) and group (p = .200, BF_{10} = .592); speed variance left to right at time (p = .618, BF_{10} = .329), and time*group (p = .205, BF_{10} = .335); NA02 left to right at time (p = .809, BF_{10} = .397), time*group (p = .583, BF_{10} = .228) and group (p = .206, BF_{10} = .696); logarithm front to rear at time (p = .742, BF_{10} = .365), time*group (p = .179, BF_{10} = .156) and group (p = .790, BF_{10} = .406); range front to rear at time (p = .274, BF_{10} = .675), time*group (p = .523, BF_{10} = .317) and group (p = .522, BF_{10} = .458); variance front to rear at time (p = .353, BF_{10} = .516), time*group (p = .383, BF_{10} = .261) and group (p = .426, BF_{10} = .511); speed variance front to rear at time (p = .958, BF_{10} = .343), time*group (p = .153, BF_{10} = .135) and group (p = .964, BF_{10} = .408); NA02 front to rear at time (p = .854, BF_{10} = .331), time*group (p = .571, BF_{10} = .249) and group (p = .188, BF_{10} = .751).

In the closed eyes condition, none of the following differences were significant: logarithm at time (p = .218, BF_{10} = .721), time*group (p = .790, BF_{10} = .474) and group (p = .222, BF_{10} = .640); ellipse at time (p = .146, BF_{10} = .897), time*group (p = .837, BF_{10} = .700) and group (p = .263, BF_{10} = .838); slope at time*group (p = .601, BF_{10} = .461), and group (p = .856, BF_{10} = .005); LFS at time*group (p = .145, BF_{10} = .591) and group (p = .448, BF_{10} = .264); average speed at time (p = .132, BF_{10} = 1.000), time*group (p = .880, BF_{10} = .444) and group (p = .673, BF_{10} = .438); speed variance at time (p = .374, BF_{10} = .484), time*group (p = .612, BF_{10} = .241) and group (p = .382, BF_{10} = .492); logarithm left to right at time (p = .603, BF_{10} = .177), and time*group (p = .867, BF_{10} = .397); range left to right at time (p = .108, BF_{10} = 1.000), time*group (p = .936, BF_{10} =

.882) and group (p = .184, BF_{10} = .934); variance left to right at time (p = .169, BF_{10} = .727), time*group (p = .947, BF_{10} = .616) and group (p = .240, BF_{10} = .796); speed variance left to right at time (p = .601, BF_{10} = .327), time*group (p = .852, BF_{10} = .370), and group (p = .083, BF_{10} = 1.000); NA02 left to right at time (p = .396, BF_{10} = .495), time*group (p = .650, BF_{10} = .266) and group (p = .739, BF_{10} = .451); logarithm front to rear at time (p = .149, BF_{10} = 1.000), time*group (p = .761, BF_{10} = .465), and group (p = .563, BF_{10} = .434); range front to rear at time (p = .381, BF_{10} = .461), time*group (p = .862, BF_{10} = .215) and group (p = .971, BF_{10} = .494); variance front to rear at time (p = .517, BF_{10} = .386), time*group (p = .960, BF_{10} = .213) and group (p = .786, BF_{10} = .527); speed variance front to rear at time (p = .189, BF_{10} = .862), time*group (p = .974, BF_{10} = .356) and group (p = .728, BF_{10} = .420); NA02 front to rear at time (p = .214, BF_{10} = .608), time*group (p = .080, BF_{10} = .426) and group (p = .130, BF_{10} = .669).

HRV. RR intervals at time*group (p = .347, BF_{10} = .714), group (p = .355, BF_{10} = .001); SDNN at time*group (p = .863, BF_{10} = 1.000); SDNN at time*group (p = .863, BF_{10} = 1.000); RMSSD at time*group (p = .378, BF_{10} = 1.000); LF at time (p = .262, BF_{10} = .130), time*group (p = .897, BF_{10} = .339); LF/HF ratio at time (p = .527, BF_{10} = .633), time*group (p = .068, BF_{10} = .122), group (p = .801, BF_{10} = .478); SD1 at time*group (p = .378, BF_{10} = 1.000); SD2 at time*group (p = .880, BF_{10} = 1.000); SD ratio at time*group (p = .431, BF_{10} = 1.000); $\alpha 1$ at time*group (p = .687, BF_{10} = .755), group (p = .213, BF_{10} = .066); $\alpha 2$ at time (p = .664, BF_{10} = .039); and sample entropy at time*group (p = .157, BF_{10} = .412), group (p = .959, BF_{10} = .304) did not change significantly.

Synthèse des résultats principaux

L'étude ENACT avait trois objectifs principaux : (1) investiguer l'impact des changements répétés de gravités incluant la microgravité sur les réponses psychologiques, physiologiques et sensorielles de sujets non-astronautes ; (2) évaluer la récupération à une semaine post vol ; et (3) évaluer la pertinence d'un fonctionnement parasympathique élevé en ligne de base en tant que biomarqueur d'adaptation pour des individus n'ayant pas suivi d'entraînement à la sélection et à l'espace.

Outre le voyage en lui-même, nous avons mis en évidence que sur une brève période, il n'existe pas un impact majeur sur la santé, telle que mesurée dans cette étude, mais un réel besoin de préparer les équipages au retour. En conséquence, il semble utile de penser le déploiement de modules de préparation avant le départ afin de préparer les futurs touristes spatiaux à anticiper leur retour sur Terre. Au minimum, cette préparation devrait informer de la difficulté à reprendre une vie quotidienne dans les jours qui suivent le vol pour que chaque touriste puisse penser à comment ajuster son activité à son état psychophysiologique post-expérience spatiale. Des astronautes ont par le passé alerté sur la nécessité de penser l'après-mission en raison de son impact psychologique. La vie peut paraitre moins brillante après s'être rapproché des étoiles.

Lors de missions de plus longue durée, telle que les vols spatiaux de longue durée (*long duration space flight*, LDSE), un des enjeux pour l'équipage sera de faire face aux menaces ponctuelles qui se présenteront. Celles-ci pourront provenir d'une défaillance technique et/ou d'une erreur humaine, soit internes à la station ; ou d'un évènement météorologique, et ainsi externe à l'équipage. Parmi ces évènements externes, le risque biologique, chimique et/ou nucléaire (i.e., risques nucléaires, radiologiques, biologiques, chimiques ou *chemical, biological, radiological and nuclear*, CBRN) doit être pris en compte. Il ne sera pas possible de prédire son arrivée, ni de le contrôler. Certes, il sera nécessaire de préparer les équipages à y faire face, en ayant recours à un entrainement voire à des simulations, pour confronter les membres au panel de situations à risque qu'ils pourront rencontrer. Les équipages étant autonomes, leur survie dépendra des mesures déployées pour y répondre et permettre le maintien opérationnel de la mission et ainsi son succès. Ces situations peuvent conduire à une réponse de stress aigu, impliquant notamment la réponse du système nerveux autonome (*autonomous nervous system*, ANS). En fonction de la nature de la réponse de stress, de la durée de la perception de la menace ou de la demande qu'elle nécessitera, et de sa persistance, les répercussions sur l'organisme sont probables. Un enjeu important est d'évaluer dans quelle mesure les réponses psychologiques, cognitives, physiologiques et extéroceptives seront impactées par une situation critique. Celles-ci impliquent de plus la menace invisible d'un environnement à risque CBRN, dont il faut se protéger en utilisant une tenue renforçant l'isolement et qui perturbe les gestes techniques appris à l'entrainement pour répondre de façon adaptée aux demandes de la situation critique. A cet enjeu, il convient d'ajouter celui de mieux évaluer le temps nécessaire pour récupérer de l'épisode stressant, un aléa ne protège pas de la survenue d'un suivant. Un corpus étoffé de la littérature dans le contexte militaire et les urgences médicales apporte certaines informations pour étudier les risques de ces situations porteuses de stresseurs multiformes. Toutefois, aucune étude n'a réellement apprécié la dimension multifactorielle du stress ainsi que sa dimension récupératrice en environnement isolé et confiné (*isolated and confined environment*, ICE) et/ou extrême et inhabituel (*extreme and unusual environment*, EUE) en y intégrant la menace environnementale de type CBRN.

C'est dans ce contexte que nous avons mené deux études pour caractériser le danger inhérent aux missions spatiales : une première étude (ANTIDOTE) évaluant les implications physiologiques, psychologiques et olfactive de l’anxiété anticipatrice au cours de simulations au risque CBRN chez des experts ; une seconde étude (RAD’LÔ) évaluant les réponses psychologiques, physiologiques, cognitives et sensorielles, incluant l’olfaction, au décours d’une simulation de survie en mer chez des experts de la navigation et des non-experts.

La première étude ANTIDOTE avait pour objectifs : (1) investiguer l'impact de l'anxiété anticipatrice chez des experts devant gérer une situation problème simulée en ambiance CBRN, en termes psychologique, physiologique et sensorielle ; et (2) étudier l’impact de cette anxiété anticipatrice sur la récupération post simulation CBRN. La récupération cible le lendemain des simulations en se focalisant particulièrement sur la conscience corporelle et la fatigue.

Afin de répondre à ces objectifs, nous avons choisi d’étudier un modèle professionnel qui implique le risque CBRN dans l’exercice du métier, celui des soignants de l’urgence que sont les soignants de la Brigade des sapeurs-pompiers de Paris. Il s’agissait de pouvoir travailler avec des professionnels ayant un niveau élevé de compétences et d'expérience en ambiance CBRN afin de pouvoir proposer une extension des résultats à la population des astronautes. Ces soignants sont formés à la prise en charge des urgences médicales mais malgré un effort de formation au risque CBRN, travailler en ambiance CBRN dans une situation critique est rare alors même que la qualité de leur prise en charge médicale dans cette environnement CBRN constitue un facteur clé de la réussite de la mission. Ces conditions sont propices à l’émergence d’une anxiété anticipatrice possiblement délétère pour la mission.

La contrainte CBRN chez ces professionnels implique qu’ils soient formés pour : (1) reconnaître un événement CBRN, (2) soigner les victimes dans une zone contaminée, autrement dit appliquer des gestes techniques dans une situation dégradée, (3) identifier l'agent pour déterminer l'antidote approprié, et (4) réduire le risque de contamination pour assurer la sécurité des équipes sur place (Olivieri, 2017). Le milieu CBRN nécessite l’utilisation d’un équipement de protection personnelle (*protective personal equipment*, PPE) qui, en plus de générer des conditions de travail difficiles (e.g., restriction des mouvements, augmentation de la température corporelle, perte de sensibilité), isole les membres de l’équipe. Ce dernier peut être rapproché des scaphandres utilisés dans le cadre des sorties extra-véhiculaires (*extra-vehicular activity*, EVA). Les simulations sont nécessaires pour permettre une meilleure appréhension du travail sous contrainte en PPE. Lors d'incidents caractérisées, les gestes à effectuer nécessiteront une finesse d'exécution importante avec un temps de réalisation limité. Plus les simulations réalisées seront de haute-fidélité en reproduisant un nombre suffisant de stresseurs, plus les équipages seront préparés à faire face et ainsi prêt à affronter la menace CBRN. Pour autant, cela nécessite que les programmes de mises en situation dans le cadre de la formation soient suffisamment complets, mais également que l'on connaisse plus avant le décours de la réponse de stress du sujet pour ajuster les modalités de préparation et de récupération.

Dans ce cadre, nous nous sommes intéressés à l'anxiété anticipatrice.

Nous posons l'hypothèse que l'anxiété anticipatrice est associée à une dégradation des réponses psychologiques, physiologiques et sensorielles et que plus elle est importante moins bonne est la récupération.

Physiological and Psychological Implications of Anticipatory Anxiety in First Responders during a CBRN Risk Simulation

En révision[8]

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Abstract

Introduction. Delivering medical support in a constrained environment presents multiple challenges given the complexity of medical care required and the stressors that health professionals will face. Literature highlights accidents with Chemical, Biological, Radiological and Nuclear (CBRN) components can generate intense psychological and thermal stress for medical teams, leading to decreased performance and compromising both victims and caregivers. Anticipatory anxiety would be an aggravating factor. The functional costs of the stressors inherent in extremes situations may have deleterious effects on health care personnel. Thus, the objective of this study is to evaluate, according to their anticipatory anxiety, the stress response health professionals in the Paris fire service during a simulated casualty triage in a CBRN environment.

Method. Twenty-seven members of the Paris Fire Brigade medical team participated in a week of training in the management of casualties in a CBRN environment, which ended with three simulations exercises. Psychological, physiological and exteroceptive measurements were made at the beginning of the training (baseline), before (pre) and after (post) the simulations as well as the day following (recovery).

Results. A k-means highlighted two profiles based on the psychophysiological functioning at baseline: Anticipatory Anxiety (AA, n=15) and Non-anticipatory Anxiety (NA, n=12) profile. Results reveal an impact of anticipatory anxiety on the psychophysiology and sensorimotor functioning on the CRBN simulation responses. The AA profile perceives more stress, and both HRV and proprioception were impacted after the simulations when compared to the NA profile. At recovery, the AA profile showed a greater need for sleep than the NA profile.

Conclusion. These results raise the question of the risk to both the victims and the medical team. Providing resource support and efficient training to teams operating in a harsh and stressful environment is essential, especially to individuals most prone to exhaustion. The outcome of a CBRN accident depends on the ability to maintain performance at the highest level over time.

Figure 18
Graphical abstract ANTIDOTE

Keywords

Anticipatory anxiety, CBRN, Extreme, Health, Heart rate variability, Neurosciences, Simulation, Stress

1. Introduction

In the last decade, the proliferation of conflicts throughout the world have made the threat more present and even constant. The advent of technology has contributed to the emergence of new disasters that are difficult to perceive, with Chemical, Biological, Radiological and Nuclear components (CBRN).

1.1. Consideration of CBRN risk

A CBRN incident may be either accidental or deliberate and consists of the release and dissemination of CBRN agents, constituting a major risk for States at the international level [1]. The nuclear power plant of Zaporijia in Ukraine has been targeted by Russian strikes since the end of July 2022, raising fears of a major incident that would not only concern the two warring parties but potentially affect the entire international community. The repercussions for international populations from the release of radioactive substances into the air (e.g., deaths, cancers, thyroid problems), is a major threat. Although such events remain occasional, several cases have been recorded [2, 3]. In 1994, the Japanese cult Aum Shinrikyo used sarin in a residential area of Matsumoto and in 1995 in the subway in Tokyo [4, 5]. In 2001, *bacillus anthracis* spores were mailed to various political and media figures in the United States [6]. Iraq and Syria have recently used biochemical agents (e.g., sulfur, chlorine, blistering agent, anthrax) against their populations on several occasions [7–11].

Agents used in CBRN attacks pose new concerns, both for the management of victims and the health of first responders, as well as for the safety of surrounding populations. After an attack, the response of medical personnel depends on several factors (e.g., magnitude, target, materials, release, exposition length). In many cases, trauma caused by these attacks constitutes an emergency that requires multiple and complex responses from medical teams. For example, a release of anthrax spores from the air over an urban area could result in 100,000 deaths [12]. First responders, such as doctors, nurses, pre-hospital medical teams and law enforcement agencies, play a major role when a CBRN event occurs. Their first actions are decisive in limiting the contamination of victims, avoiding the transfer of an agent from the emergency chain to hospitals and reducing the risk of transmission to the population [13]. It is therefore imperative that all health care professionals, especially first responders, should know how to respond effectively. In

2019, Calamai et al. [14] conceptualized the CBRN chain of survival for the management of victims in the first hours following an incident. This chain is composed of five links that comprise the essential actions: (1) emergency decontamination, (2) symptom analysis and toxidrome testing, (3) early administration of antidotes, (4) thorough decontamination, and (5) evacuation to the hospital. The first link is critical to the management of CBRN risk and its evolution [15]. The earlier it is handled, the more the risk of contamination and the degree of toxicity of the agent can be reduced. The first two links in the chain can be managed by non-specialists (i.e., Basic Life Support) but the last three links require the intervention of a specialized medical team (i.e., Advanced Life Support). In order to facilitate its memorization by the teams, the CBRN chain is described by the acronym « I AM THOR », standing for Immediate decontamination (I), Assessment (A), Medication (M), Through decontamination (TH), Hospital (O), Reevaluation (R) [16]. However, the anxiety-provoking and dangerous environment in which medical teams evolve necessarily impacts on the psycho-physiological state of the workers, independent of the risk related to the CBRN agent.

1.2. A stressful environment for health professionals

A CBRN event results in increased stress levels for an emergency medical team. By its nature, such an event is unusual, and will pose a uniquely life-threatening risk due to the environment that develops around it. Wearing Personal Protective Equipment (PPE) is an additional stress factor since it alters exteroceptive information and isolates the care actors from each other. The literature has shown that a state of stress has an impact on cognitive performance [17, 18], notably decision making [19–24]. First responders under extreme stress must first and foremost have strategies (i.e., on the front line and in the hospital) designed to reduce the morbidity and mortality of exposed individuals and limit the risk to workers and health care facilities [25]. This outcome requires a high level of performance (e.g., decision making, responsiveness, multi-tasking, mental workload) from healthcare professionals, whether or not they are delivering care [26]. Studies have shown a decrease in cognitive and communicative performance amongst medical teams during simulation exercises [18, 27–30]. Exposure to the constraints and risks of a CBRN event is not without consequences for the psyche either. First responders are highly exposed to life-threatening and potentially traumatic events, and thus there is a clear risk of developing Posttraumatic Stress Disorders (PTSD) [31, 32]. Most studies on the psychological impact of crises for first responders do not concern CBRN incidents or attacks but rather terrorist attacks [33, 34]. Thus, following the Paris attacks in 2015, the prevalence of the development of PTSD is estimated at 4.8% in its complete form and 15.7% in its partial form in first responders [35]. Nevertheless, PTSD is only one of many possible mental disorders [34, 36]. The terrorist attacks in Japan with the chemical nerve agent sarin have showed an increase in the level of anxiety and fear, and the emergence of psychiatric pathologies among first responders [34, 37–39]. Furthermore, lack of sleep and fatigue enhance the negative effects on performance [40–42], and can lead to errors [43, 44]. Chronic sleep deprivation, as the above studies show, is likely to increase the difficulty of work.

Surprisingly, to our knowledge, the impact of the PPE on the senses has not been studied. In particular, the impact of PPE on smell is unknown. This seems an oversight since, on the onde hand a strange smell is an indicator of a CBRN attack and on the other, stress and associated emotions, such as fear, can alter odour perception, by intervening from the sensor (peripheral nervous system) to the interpretation of the sensory input (brain) [45]. At multiple stages, the level of performance is compromised by the wearing of PPE. Composed of a breathing apparatus and chemical protective suits, its role is to protect them against any possible contamination. Kim et al. [43] found a decrease in the performance of life-saving interventions (i.e., cardiopulmonary resuscitation, intravenous cannulation, endotracheal intubation) related to the constraints of PPE. It also increases the level of stress and is likely to alter communication between members [27–30]. Merchan and Clemente-Suárez [46] conducted a study to investigate the impact of PPE gear on psychophysiological and sensorimotor response during an assault maneuver. They reported a decrease in movement speed, and an increase in heart rate, body temperature, somatic anxiety, and subjective perception of exertion. Due to limited thermoregulation, PPE may expose the wearer to the risk of exhaustion and elevated cardiac stress [47], through increased cardiovascular strain, core body temperature, and hypohydration [27, 48]. Rayson [49] found an increase in core temperature of +1.6°C in practicing firefighters. Other authors have observed similar changes. Several participants had to be removed from protocols because of exhaustion or because they reached the safe core body temperature threshold of 39°C or higher [27, 50–53]. Some have suggested that an increase in body temperature contributes to a performance deficit [27, 54]. Thus, heat stress leads to a significant decrease in performance, which may have repercussions on the quality of care first responders deliver.

In this way, the response of medical teams to a CBRN incident in an operational field involves a complex interaction of factors that compound over time, including the stress of dealing with emergencies, fatigue, lack of sleep, and inadequate nutrition. Lack of experience, a low proportion of trained personnel, the unusual nature of this type of intervention, and the constraints involved in wearing PPE will be highly stressful additional factors. Repeated exposure to stress can also lead to insufficient recovery, which can increase fatigue levels and lead to cumulative burnout among personnel [55, 56]. Overall, these data have recently led some researchers to posit a need to conduct research aimed at improving the work of CBRN-type crisis professionals by increasing physical and cognitive abilities, as well as heighten sensory awareness [57].

1.3. Anticipatory anxiety in stress regulation

The response to stress is regulated by the Autonomic Nervous System (ANS) which allows an individual to respond appropriately to perceived or real danger. A multifactorial response ensues, resulting in changes in the visceral functions of the body (e.g., heart contractions, blood vessel constriction, blood pressure, digestion, regulation of body temperature through sweat gland production, pupillary dilation, lung capacity). Stress leads to important behavioral changes and alters psychophysiological homeostasis and cognitive responses. Conversely, the anxious response includes emotional responses triggered by the anticipated perception of a threat, and thus the associated recurrent thoughts [58]. Anxiety is considered a fundamental emotion and is associated with defense mechanisms [59]. Anticipatory anxiety is a « complex combination of a future-oriented cognitive state, negative affect, and autonomic arousal » [60]. This is associated with a strong physiological arousal leading to increases heart rate [61–63], respiratory rate [64, 65], skin conductance level [66], an hypervigilance towards potential threat, excessive worry, uncertainty [67, 68], and a clear potentiation of the startle reflex [68–70]. Thus, anticipatory anxiety is related to concerns about unpredictable aversive situations and threats perceived by the individual. At the brain level, anticipatory anxiety has been linked to the activation of stress networks that stimulate the arousal and negative affect, such as fronto-limbic circuits [60, 71–80]. While the literature indicates that close links exist between anticipatory anxiety and the fear reaction [81–84], it is clear that there is no consensus on the most relevant biomarker to measure it. It has been mainly studied in the context of PTSD [85, 86] or phobias [87–91] due to the psychosomatic behaviors it generates (e.g., avoidance, hypervigilance, negative affect). Recent studies related to the Covid-19 pandemic have shown that anticipatory anxiety in many health professionals, linked to the uncertainty of the situation and having repercussions on their psychological state [92–96]. Although the relationship between unpredictability, as uncertainty about future negative events and anxiety, makes intuitive sense the association between them has been less studied.

Anticipatory anxiety is classically associated with lower cognitive performance, including cognitive control processes and inhibitory functioning [97, 98] related to a higher stress response [99]. In particular, anticipation of an unpleasant stimulus has been associated with a reduction of heart rate based on a parasympathetic inhibition of it [99, 100]. In this case, heart rate autonomic regulation could be a biomarker of anticipatory anxiety resulting at most in a « freezing response » [99]. However, further research is needed as there are few data studying heart rate autonomic and anticipatory anxiety (e.g., interindividual variability of the anticipatory anxiety). Based on an anticipatory anxiety task study, Barrett and Armony [101] reported that anxiety-trait, assessed by a psychometric tool, is associated to dissociate cognitive-physiological responses. Whereas anxiety-trait is associated with a faster cognitive response for high anxiety-trait subjects for the anticipatory anxiety task, no difference is observed between anxious and non-anxious people for the autonomic system response. Also, in a study evaluating the effects of posture on anticipatory anxiety, results showed that standing position was associated with higher stress and anxiety [102]. Furthermore, it has been shown that anxious people experience more anticipatory anxiety and an increase of stress when the stressor is uncertain [103]. Uncertainty is associated with increased physiological reactivity and greater recruitment of brain regions that promote arousal and stress [103, 104]. Similarly, it has been shown that individual differences in the capacity to tolerate uncertainty were not related to anticipatory startle responsivity [103] but to a high anticipatory parasympathetic activity [100]. At present, there is no consensus on the characterization of inter-individual variability in anticipatory anxiety. On one hand, the available literature uses either psychometric anxiety assessments or physiological measures to discriminate anticipatory anxious subjects. On the other hand, it evaluates how a psychometric profile of anticipatory anxiety impacts the physiological stress response. Nevertheless, self-questionnaires use limited Likert-type scaling that includes interval responses, whereas biological outcomes are continued and most often not linear [105].

1.4. HRV as a physiological marker of stress and anticipatory anxiety

Heart Rate Variability (HRV) is the variation in time between each heartbeat. Over the years, HRV has become widely accepted as an objective marker of an individual's stress response [106]. This physiological function represents the level of activation of the ANS. More specifically, the ANS is divided into two branches: the Sympathetic Nervous System (SNS) (i.e., associated with activity and a state of intense stress leading to an increase in heart rate) and the Parasympathetic Nervous System (PNS) (i.e., associated with a state of calm and relaxation leading to a decrease in heart rate) [107]. These contribute to the maintenance of the adaptive homeostasis of the organism, with interindividual differences [108, 109]. It has been established that the sympathetic and parasympathetic branches function in a reciprocal manner (i.e., an activation of one branch of the ANS leads to a decrease in the activity of the other) [110]. Nevertheless, in certain circumstances, the two branches of the ANS can be coactive, the SNS and the SNP evolve in a joint manner [99]. When SNS is increased, activation of the PNS results in inhibition of heartbeat acceleration, which in turn reduces heart rate. Currently, the literature emphasizes the role of parasympathetic activity as a stress brake [111–113]. HRV analysis can be differentiated into time, frequency and non-linear domains. Time domain values measure the amount of HRV observed during a given time period. Frequency domain values calculate the power distribution in different frequency bands. Nonlinear parameters measure the unpredictability and complexity of a series of intervals between heartbeats [114]. These indices have been proposed to characterize the dynamic properties of the HRV that other methods cannot transcribe [115].

HRV can thus reflect the level of physiological and psychological stress of an individual [114, 116, 117]. Porges [118] noted that HRV reflects both chronic stress and vulnerability to stress. Thus, variation in HRV may reflect the resistance of the body and mind to a psychological or physical stressor, and cardiac biosignals could be an indication of an adaptive response to changing environmental conditions. Its decrease has been associated with the occurrence of cardiovascular disorders [119–121], vascular diseases [122–125], psychological disorders, and cognitive impairments [120, 126–131]. It is also a valid method for objective workload monitoring. Recently, a study by Thielmann et al. [132] highlighted HRV as an objective indicator of mental stress in emergency physicians. Neufeld et al. [133] measured HRV and sleep in emergency medical technicians. Those working on a full-time schedule had shorter, fragmented sleep associated with increased sympathetic activity and decreased parasympathetic activity. Recent years have seen the validation of this physiological signal in the military [134–136], and its interaction with anticipatory anxiety [134, 137–142]. Delgado-Moreno et al. [140] analyzed the psychophysiological response during a combat simulation in fifteen experienced soldiers from a special operations unit and twenty inexperienced soldiers from a Spanish Army light infantry unit. Results showed that simulation-induced stress produced a significant increase in perceived exertion, anxiety, and HRV Low Frequency (LF), and a decrease in performance, and HRV High Frequency (HF). Anticipatory anxiety in experienced soldiers demonstrated a cognitive-behavioral association with past experiences. Similar results were found by Sánchez-Molina et al. [142]. These authors analyzed the psychophysiological and sensorimotor response in twenty elites and twenty-four non-elite soldiers of the Spanish Army during a simulated evacuation of a soldier from a conflict zone. Results show that elite soldiers had a higher metabolic, cardiovascular, and anxiety response than non-elite soldiers. Each soldier experienced anticipatory anxiety manifested by increased sympathetic modulation and while non-elite soldiers showed increased sensorimotor responses. Overall, elite soldiers did not show a more efficient psychophysiological response than non-elite soldiers despite having more training and experience.

Thus, HRV is a potentially useful stress monitoring tool. Its use to survey acute stress, including anticipatory anxiety, and recovery responses in first responders and tactical operators appears to be operational [143].

1.5. CBRN training to save lives

Over the past few years, an increasing number of training courses have emerged on the international scene to train medical teams for CBRN risk. The ability of medical teams to respond appropriately in the event of a CBRN incident is dependent on - and cannot be separated from - effective training to raise awareness and develop expertise in CBRN risk management. Furthermore, team readiness is not limited to the acquisition of skills but extends to the degree of confidence individuals feel in the training they have received [144]. Their performance in the field in an operational crisis can only be enhanced.

Most studies describe inadequacies in the level of training of health professionals [145–159]. It is important to emphasize that this is the case regardless of the country in which the training takes place (e.g., England, USA, Canada, Greece, Pakistan, China, Japan, Australia) and that on average 30% of the people included in the research believe that they have received training. This discrepancy suggests that the nature and extent of training need reassessing [160–163]. It should also be noted that teams seem to be better trained in chemical and biological risk than in nuclear and radiation risk [149]. This results in high levels of subjective stress in relation to CBRN disasters [148]. Research is therefore trying to define specific training needs [164, 165]. Areas in which caregivers are most deficient include communication, drills, multiple casualty incidents and CBRN accidents [165]. The literature suggests however that training varies greatly from country to country and from institution to institution [13, 166, 167]. Consequently, it is difficult to establish recommendations about the most effective approach.

Scenario-based simulations seems to be the most effective [168, 169], providing a rich sensory experience that allows healthcare professionals to use their knowledge and acquired skills in a lifelike CBRN context [13]. Since January 2021, the Paris Fire Brigade (BSPP) has been using a cognitive tool named « I AM THOR » at the heart of its CBRN risk training designed to help first responders to memorize the actions to be performed in the event of an incident. The purpose is to facilitate decision making and enhance reactivity to the needs generated by uncertain but dangerous circumstances [14, 170] The chain of survival is used to determine PPE management; the symptoms based on agents; therapeutic management and the antidotes to be administered; and the decontamination and the evacuation of victims. It is also used during debriefing following simulation exercises. These exercises involve interactive patient mannequins connected to a laptop and monitor that creates a CBRN scenario. During which a patient's condition can be improves or deteriorates over time [171]. The exercises attempt to replicate as nearly as possible the circumstances of a CBRN incident and so address the emerging need to increase health professionals' knowledge of the appropriate protocols.

The more in-depth their training, the greater the likelihood that they will be able to respond appropriately in the event of an incident and reduce the risk of morbidity and mortality for both the medical teams and the victims involved. The outcome of a CBRN incident thus depends on their level of preparedness.

1.6. Context of the experiment

A better understanding of the mechanisms at work among professionals under stress of CBRN situations is fundamental in order to: (1) provide a safe environment for medical teams acting in the field of operations; (2) to improve the care provided to victims; (3) to reduce the risk of contamination of first responders and populations; and (4) to decrease the risk of burnout among health professionals. Adequate, and personalized training in the CBRN chain is essential to meet the challenges posed by a CBRN attack, the BSPP decided to provide complete and high-level training for its health professionals. The aim of this study is to evaluate the impact of anticipatory anxiety among health professionals of the Paris fire department during simulated interventions involving victims in CBRN operations that took place during a CBRN week of training for these first responders. Its general objective is to describe the impact of CBRN simulations exercises on psycho-cognitive, physiological, and exteroceptive abilities according to the anticipatory anxiety status. The specific aim is twofold: (1) to evaluate the impact of anticipatory anxiety during CBRN incident simulations on psychological, physiological, and exteroceptive abilities; and (2) to assess anticipatory anxiety on body awareness and fatigue recovery abilities in this challenging environment. The key hypothesis is a negative impact of anticipatory anxiety on psychological, physiological, and exteroceptive abilities during the CBRN simulations and on recovery. We choose to evaluate the anticipatory anxiety using both an HRV tonic and psychometric assessment of anxiety state at the beginning of the CBNR training.

2. Materials & Methods

2.1. Design

This study (2021PPRC-15) was approved by committee for the protection of individuals (CPP Sud-Est VI, Clermont-Ferrand; France) and was conducted according to the standards of the Declaration of Helsinki. After comprehensive verbal and written explanations, all participants gave their written consent to participate.

2.2. Participants

Participants were 28 healthy firefighters from the BSPP. Their health status was confirmed by their aptitude to fit with the last periodic medical check-up. The exclusion criteria were: (1) participation's decline in the study; (2) heart rhythm disorder; (3) endocrine pathology (e.g., hyperthyroidism, diabetes); (4) arterial hypertension; (5) current pregnancy or breast-feeding; (5) anti-inflammatory treatment; (6) treatments interfering with heart rate (e.g., beta-blockers, calcium antagonists, alpha1-receptor agonists); (7) psychotropic treatments. One participant was excluded from the study for medical reasons during the experiment, resulting in 27 subjects (6 women and 21 men, Mage = 31.90 ± 7.0 years, ranging from 21 to 53). Among health professions, ten (37.03%) were drivers, seven (25.92%) were nurses and 11 (40.74%) were doctors. Their professional experience ranged from 13.40 ± 2.87 years for divers, 4.29 ± 2.62 years for nurses, and 9.20 ± 7.31 years for physicians. Drivers had spent 13.40 ± 2.87 years, nurses 2.21 ± 3.43 and physicians 1.89 ± 1.16 in BSPP. Among the six women, four of them (14.81%) used a contraception (i.e., pill, copper intrauterine device). None of the participants had any current medication. Five of the participants (18.51%) were smokers. One participant (4.76%) had a pneumothorax in the past. Nine participants declared major stress events in their past (33.33%). Ten (37.03%) declared using a stress management technique occasionally (i.e., meditation, self-hypnosis, cardiac coherence, autonomous sensory meridian response). The average height of participants is 175.00 ± .00 meters, and weight is 75.51 ± 13.85 kilos.

Table 1 reported the socio-demographic characteristics of participants.

Table 1

Socio-demographic characteristics of participants

Measurements	Data*
N	27
Mage	31.90 ± 7.0
Mheight	175.00 ± .00
Mweight	75.51 ± 13.85
Gender (women/men)	22.22%/77.77%
Contraception	14.81%
Smokers	18.51%
Major stress events	33.33%
Stress management technics	37.03%

*Mean and standard deviation are reported when necessary. Other index show the ratio of the number of subjects.

2.3. Data collection

The socio-demographic questionnaire (28 items) is a handmade questionnaire used to collect general information on family situation, medical history, current health status and hobbies.

2.3.1. Psychological measurements

The State Trait Anxiety Inventory (STAI-Y version B) was designed to assess the feelings of apprehension, tension, nervousness, worry that the subject feels at the time of the stress situation (20 items) [172]. The Scale of Positive and Negative Experience (SPANE) assesses subjective feelings of positive and negative affects, based on how frequently they were felt at the present moment (12 items) [173]. The scale is divided into two sub-factors: positive and negative affects. The Freiburg Mindfulness Inventory (FMI) measures mindful disposition (14 items). The scale is divided into two sub-factors: presence and acceptance without judgment [174]. The Multidimensional Assessment of Interoceptive Awareness (MAIA-2) evaluates interoceptive awareness (32 items) [175]. The scale is divided into eight sub-factors that measure awareness of uncomfortable, comfortable, and neutral body sensations, the response to sensations of pain and discomfort, the ability to regulate attention to body sensations, and awareness of mind-body integration (i.e., noticing, not distracting, not worrying, attention regulation, emotional awareness, self-regulation, body listening, trusting). The Postural Awareness Scale (PAS) is a questionnaire assessing body posture awareness (12 items) [176]. The scale is divided into two sub-factors: ease/familiarity with postural awareness and need for attention regulation with postural awareness. The NASA Task Load Index (NASA-TLX) is a questionnaire designed to measure and perform a subjective assessment of mental load (6 items) [177]. The Buguet sleep questionnaire was used to evaluate overall status after sleep and divided into five subscales: sleep quality, need for sleep, physical shape, moral health andmood (10 items) [178].

2.3.2. HRV

Heartbeat interval data (RR) were recorded for a five-minute period, with subjects in a sitting position, using the gold standard ECG data in an integrated system and software package (Biopac MP160, System Inc., California, USA). Each participant wore a 3-lead ECG (BN-EL45-LEADS3) configuration placed on the right chest, the left chest, and the lower left chest. An alcohol pad was used to remove the top layer of dead skin cells. Three self-adhesive disposable electrodes (2.5 cm × 2.5 cm) were placed on the above-mentioned areas. Electrodes were connected to a Biopac ECG2-R. The positive lead was attached to the left chest electrode; the negative lead was attached to the right chest electrode; the ground electrode was attached to the lower left chest. Data were recorded at a sampling frequency of 2000 Hz.

The HRV analysis was done according to the guidelines [179, 180], considering possible circadian variations, using the *PyHRV* python library [181]. The following data were also recorded: weight, height, waist-to-hip ratio, smoking habits, most recent alcohol intake (>24h), most recent caffeinated (coffee/ tea) intake (>1h), most recent meal (>2h), most recent physical activity (>12h), and quality of sleep on the day of, and the day preceding the experiment.

Raw ECG data were filtered between 3 and 45 Hz using a finite impulse response band-pass filter. The order of the filter was set at 600 (0.3 times the sampling frequency). R peaks were automatically detected using the *BioSPPy* python library [182]. Once the signal was filtered, a Hamilton segmentation was performed, followed by an R-peak correction with a tolerance set to 0.05. The validity of R wave detection was manually examined to ensure correct detection. If an ECG sequence was overly noisy when visualizing the superposition of all QRS complex, a time interval was manually removed to improve data quality. RR intervals were automatically detected with the *hrvanalysis* module using linear interpolation, and manually corrected for artifacts and ectopic beats.

Time domain analysis. Time domain HRV metrics included mean RR (mean interbeat interval), SDNN (Standard Deviation of the Normal-to-Normal RR interval), RMSSD (Root Mean Square of Successive Differences between adjacent RR intervals), and pNN50 (percentage of adjacent NN intervals that differ from each other by more than 50 ms).

Frequency analysis. Frequency domain HRV metrics complemented time domain metrics and included the properties of oscillatory components in heart rate dynamics. Spectral density was estimated using Welch's method: LF (sympathetic and parasympathetic activity) in the range 0.04–0.15 Hz, HF (parasympathetic activity) in the range 0.15–0.4 Hz, LF/HF ratio in absolute powers (ms^2).

Nonlinear analysis. Nonlinear HRV metrics reflect dynamic and chaotic internal states that other metrics cannot reflect. The most representative metrics were used: the poincaré plot (i.e., graphical representation of the correlation between successive interbeat intervals), SD1 (i.e., standard deviation of instantaneous interbeat interval variability), SD2 (i.e., standard deviation of continuous, long-term RR variability), α1 (i.e., detrended fluctuation analysis self-similarity parameter that represented short-term fluctuations), α2 (i.e., detrended fluctuation analysis self-similarity parameter that represented long-term fluctuations), sample entropy (i.e., regularity and complexity of time series).

2.3.3. Exteroceptive measurements

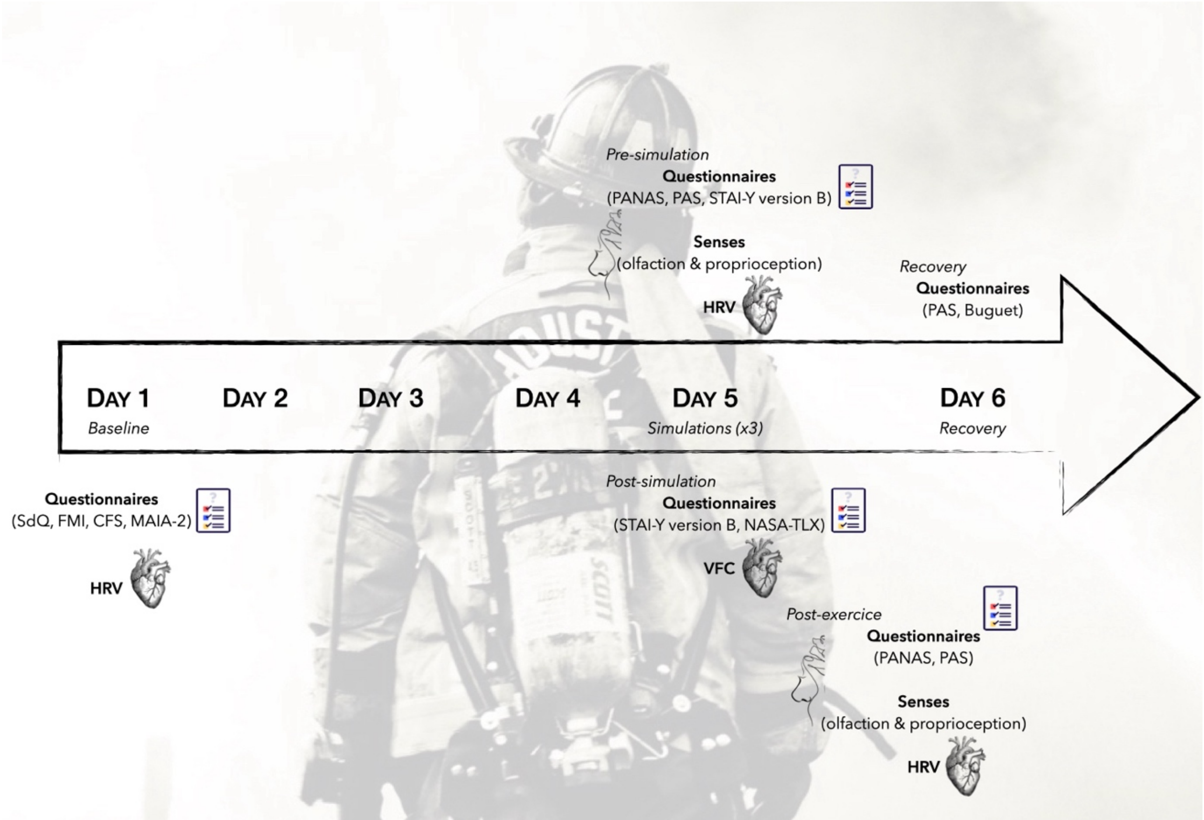
Olfaction. The European Test of Olfactory Capabilities (ETOC) assesses olfactory sensitivity [183]. Individuals are asked to select a bottle (i.e., 16 sets of four bottles) that contains a specific odor (i.e., discrimination) and state the nature of this odor (i.e., identification). Participants were also asked to evaluate the hedonic value of the detected odor.

Proprioception. Posturography was assessed using connected soles (FeetMe, Paris, France). Subjects were asked to stand for one minute with their eyes open, and one minute with their eyes closed. Among the numerous metrics regularly used to characterize postural stability in the literature, we assessed the most frequent metrics including percentage of weight distribution between the left and right foot in the front and back.

2.4. Experimental design

The study was conducted at the Val-de-Grâce School between January and April 2022 during CBRN simulation sessions, integrated into the CBRN training course of the BSPP. The objective of these sessions was to train the BSPP medical team (i.e., doctors, nurses, resuscitation ambulance drivers). The first four days of the training were dedicated to theoretical courses with some exercises on the fourth day. On the first day of the training, baseline measures were recorded (i.e., psychology, physiology, sensory) after verification of the inclusion criteria. The simulation exercises took place on the fifth and last day of course, with a crew of three firefighters implicated in each simulation. There were three simulations exercises of increasing complexity: (1) nerve agent poisoning with two victims to be treated; (2) dirty bomb with three victims; (3) hostage situation with nerve agent poisoning and five victims to be treated. Figure 1 reports an overview of the experiment.

Figure 1
Overview of the experiment



Upon arrival on the morning of the day of the simulations, participants completed a series of questionnaires assessing emotion, level of body awareness, and perceived stress prior to the simulation. The data concerning olfaction were then collected, along with the measurement of proprioception. An ECG was also recorded for five minutes in a sitting position. Participants went to be equipped with a CBRN suit composed of a level 3 polyCOMBI® filtering suit and a protective respiratory filtering device (Figure 2). They were instructed that they would have to manage several victims exposed to a chemical or radiological agent outside the hospital and implement the first tactical and therapeutic measures. After each simulation, participants completed a series of questionnaires to assess their state of anxiety, their perceived level of stress and their mental load. At the end of the day, they again completed the series of questionnaires to assess their post-simulation psychological state. Olfaction, proprioception, and ECG were again recorded. The morning after the simulations, participants completed a series of questionnaires designed to assess their recovery by evaluating their body awareness and sleep quality the previous night.

Figure 2
CBRN filtering polyCOMBI® suit

2.5. Statistical methods

The descriptive statistics were expressed as mean ± SD. Statistics were computed for all outcome measures. An unsupervised k-means clustering machine learning algorithm was applied to distinguish our population with respect to anticipatory anxiety, based on the RMSSD and STAI-Y version B scores at baseline, using Python (Python, Software Foundation, Wilmington, v3.9). Statistics for data analyses were computed for all outcome measures with JASP (JASP, Amsterdam, version 0.16.3), an open-source software running both classical and Bayesian analyses. The Shapiro–Wilk test was used to determine whether data were normally distributed. For significant analyses, the effect sizes were reported. A Chi^2 was used to explore the distribution of health professionals between profiles. Characterization of anticipatory anxiety at baseline (i.e., at the beginning of the CBRN training week) was done using one-way ANOVA or Kruskal-

Wallis when necessary. Then, in order to explore the impact of CBRN simulations on first responders in the psychological, physiological and sensory states, we used repeated-measures ANOVA. Holm post hoc analyses were performed when *p*-value reached significance. Bayesian analyses were performed applying the equivalent analyses for the repeated-measures ANOVA and one-way ANOVA. The default Bayesian Factor, noted BF10, was presented in case of no significant effect. A negative value provides support for the null hypothesis, whereas a positive value indicates evidence in favor of the alternative hypothesis [see Additional file 1]. For all analyses and results presentation, statistical significance was set at $p < .05$. A *p*-value between .05 and .07 was considered as evidence of a trend.

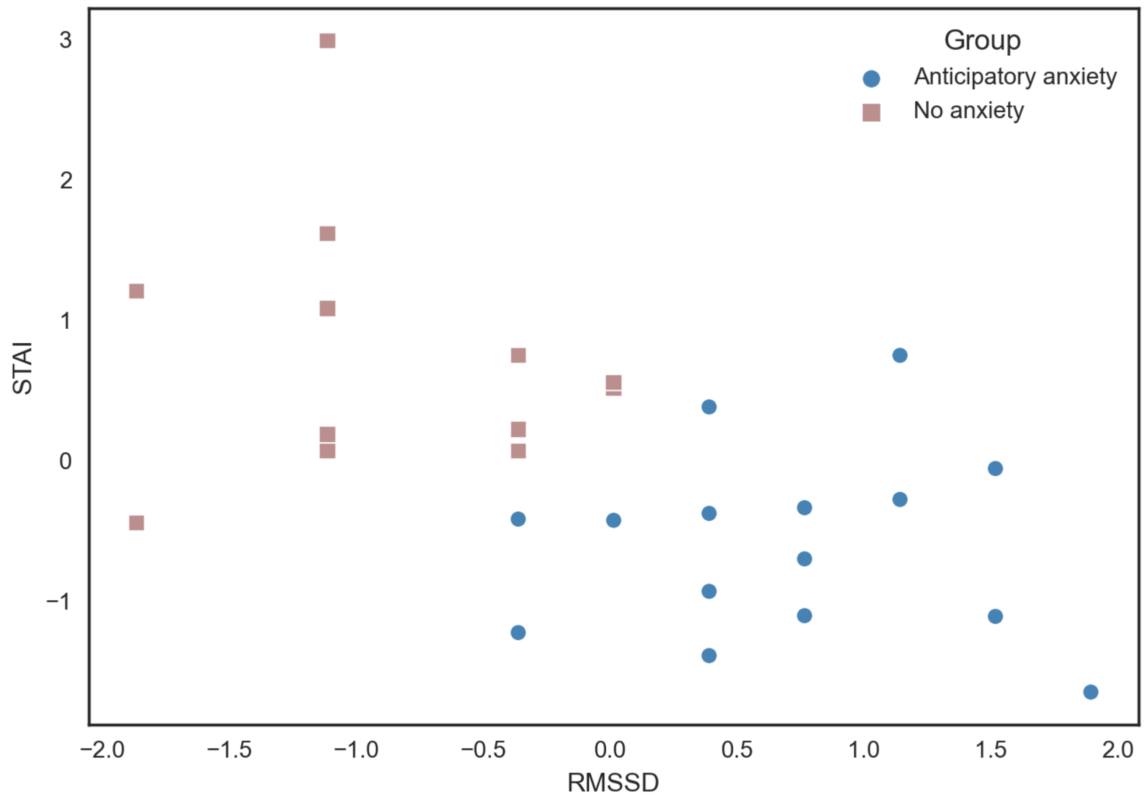
3. Results

3.1. Baseline anticipatory anxiety profiles differences

A k-means was used in order to separate our population into two profiles of anticipatory anxiety using scikit-learn, a machine learning library. These profiles were based on the STAI-Y version B (i.e., a measure of state of anxiety) and the RMSSD (i.e., a measure of the PNS activation). Data were standardized using the standard scaler package. The silhouette score (i.e., a measure of how close each point belongs to the same cluster compared to its neighbors) was used to estimate the optimal number of clusters (n=2). Then, a k-means clustering was performed and highlighted two profiles differentiated on their psychophysiological functioning: « Anticipatory Anxiety » (AA) and « Non-anticipatory Anxiety » (NA) (Figure 3). The AA profile exhibited a lower level of parasympathetic HRV functioning, characterized by a predominance of the PNS activity at rest, as well as a higher perception of subjective stress at the beginning of the CBRN training week when compared to the NA profile. Among the AA profile, 5 were physicians, 3 were nurses, and 7 were drivers compared to the NA profile in which 5 were physicians, 4 were nurses, and 3 were drivers.

Figure 3

k-means clustering on psychophysiological stress response



Psychophysiological and sensory differences at baseline among the AA and NA profiles were presented in Tables 2 to 5.

Table 2

Baseline disposition measurements among profiles

	AA (N = 15)	NA (N = 12)	*p*-value*
Mindful disposition			
Presence	18.267 ± .2.890	18.917 ± 3.315	.591
Acceptation	22.000 ± 4.583	21.333 ± 3.447	.680
Interoception			
Noticing	11.000 ± 4.259	9.583 ± 5.017	.435
Not distracting	9.867 ± 4.486	9.583 ± 5.054	.879
Not worrying	17.667 ± 4.271	14.750 ± 4.181	.087
Attention regulation	23.602 ± 3.640	20.667 ± 5.883	.124
Emotional awareness	16.086 ± 4.528	16.833 ± 7.234	.745
Self-regulation	13.072 ± 4.510	10.833 ± 4.726	.221
Body listening	6.459 ± 3.776	7.500 ± 3.503	.469
Trusting	11.753 ± 2.935	10.917 ± 4.316	.555

**p*-value used in the analysis of effects. Means and standard deviation are show for each variable. None of the variables reach the significance or a trend (p>.07).

Table 3

Baseline psychological measurements among profiles

	AA (N = 15)	NA (N = 12)	*p*-value*
Anxiety			
State	52.800 ± 1.781	48.667 ± 1.723	**< .001**
Emotion			
Negative affect	1.689 ± .577	2.014 ± .505	.137
Positive affect	4.089 ± .487	4.194 ± .324	.526
Body posture awareness			
Ease & familiarity with postural awareness	23.467 ± 6.791	21.182 ± 7.922	.437
Need for attention regulation	23.667 ± 7.037	19.949 ± 6.313	.178

**p*-value used in the analysis of effects. Means and standard deviation are show for each variable. Significant differences or trend were highlighted (p>.05).

Table 4

Baseline physiological measurements among profiles

	AA (N = 15)	NA (N = 12)	*p*-value*
HRV			
RR intervals	901.317 ± 128.163	1027.481 ± 143.907	**.024**
SDNN	57.393 ± 27.389	94.453 ± 23.256	**< .001**
RMSSD	35.165 ± 18.692	72.675 ± 25.759	**< .001**
pNN50	17.566 ± 18.016	47.854 ± 17.691	**< .001**
LF	1532.016 ± 1597.875	4680.727 ± 3360.997	**.004**
HF	528.472 ± 657.966	1961.668 ± 1650.988	**.001**
LF/HF ratio	3.923 ± 3.448	6.525 ± 7.854	.259
SD1	24.864 ± 13.217	51.388 ± 18.214	**< .001**
SD2	76.781 ± 37.116	122.376 ± 30.669	**.002**
α1	1.102 ± .278	1.018 ± .368	.505
α2	.857 ± 239	.633 ± .237	**.023**
Sample entropy	1.306 ± .275	1.337 ± .364	.801

**p*-value used in the analysis of effects. Means and standard deviation are show for each variable. Significant differences or trend were highlighted (*p*>.05).

Table 5

Baseline sensory measurements among profiles

	AA (N = 15)	NA (N = 12)	*p*-value*
ETOC			
Detection	15.429 ± .938	15.417 ± .996	.975
Identification	6.459 ± 3.776	7.500 ± 3.503	.469
Hedonic value	59.286 ± 12.869	60.000 ± 11.426	.883
Proprioception			
% of weight towards the right front (OE)	43.875 ± 9.583	55.700 ± 7.499	**.010**
% of weight towards the front left (OE)	50.000 ± 12.189	53.000 ± 10.944	.590
% of weight to the right rear (OE)	55.000 ± 10.850	44.300 ± 7.499	**.025**
% of weight to the left rear (OE)	48.875 ± 12.597	47.000 ± 10.944	.740
% of weight towards the right front (CE)	46.125 ± 8.626	57.800 ± 7.495	**.007**
% of weight towards the front left (CE)	51.250 ± 9.347	56.400 ± 11.626	.325
% of weight to the right rear (CE)	53.875 ± 8.626	41.900 ± 7.520	**.006**
% of weight to the left rear (OE)	48.750 ± 9.347	43.900 ± 11.561	.351

**p*-value used in the analysis of effects. Means and standard deviation are show for each variable. Open eyes condition (OE) and Closed eyes condition (CE). Significant differences or trend were highlighted (p>.05).

Anxiety-state. AA perceived a higher situational anxiety [F(1,25) = 36.947, $p < .001$, $\eta^2 = .596$] than NA.

HRV. AA have lower RR intervals [F(1,25) = 5.795, $p = .024$, $\eta^2 = .188$], SDNN [F(1,25) = 13.914, $p < .001$, $\eta^2 = .358$], RMSSD [F(1,25) = 19.237, $p < .001$, $\eta^2 = .435$], pNN50 [F(1,25) = 19.144, $p < .001$, $\eta^2 = .434$], LF [W = 8.432, $p = .004$, $w^2 = .257$], HF [W = 10.532, $p = .001$, $w^2 = .239$], SD1 [F(1,25) = 19.237, $p < .001$, $\eta^2 = .435$], SD2 [F(1,25) = 11.693, $p = .00$, $\eta^2 = .319$], than NA.

Proprioception. On open-eyes condition, AA have a lower percentage of weight towards the right front [F(1,16) = 8.654, $p = .010$, $\eta^2 = .351$], a higher percentage of weight to the right rear [F(1,16) = 6.121, $p = .025$, $\eta^2 = .277$] than NA. In closed-eyes condition, AA have a lower percentage weight towards the right front [F(1,16) = 9.443, $p = .007$, $\eta^2 = .371$], and a higher percentage of weight to the right rear [F(1,16) = 9.903, $p = .006$, $\eta^2 = .382$] than NA.

3.2. Impact of anticipatory anxiety profiles on psychophysiology after CBRN simulations

Emotion. For negative affect, there was a significant effect of group [$F(1,25) = 4.684$, $p = .040$, $\eta^2 = .141$]. NA profile has more negative affect than AA profile.

Anxiety-state. There was a significant effect of group [$F(1,25) = 9.119$, $p = .006$, $\eta^2 = .133$]. AA profile perceives more situational anxiety than NA profile.

Body posture awareness. For ease and familiarity with postural awareness, there was a significant effect of time*group [$F(2,48) = 3.135$, $p = .053$, $\eta^2 = .010$]. Post hoc analyses show that AA profile has a decrease in ease and familiarity with postural awareness ($p = .058$, $d = .385$) at the end of simulations compared to baseline.

HRV. Significant differences were found for linear and nonlinear index.

In *time domain*, there was a significant effect of time*group [$F(2,50) = 6.364$, $p = .003$, $\eta^2 = .060$] for RR intervals. Post hoc analyses report that NA profile has higher RR intervals at baseline compared to before ($p = .003$, $d = 1.046$) and at the end ($p < .001$, $d = 1.207$) of simulations. There were significant effects of group [$F(1,25) = 7.521$, $p = .011$, $\eta^2 = .169$], and a trend for time*group [$F(2,50) = 2.820$, $p = .069$, $\eta^2 = .026$] for SDNN. Post hoc analyses reveal that AA profile has a lower SDNN than NA profile. Moreover, AA profile tend to have a lower SDNN than NA profile at baseline ($p = .012$, $d = -1.390$), and at the end of simulations compared to NA profile at baseline ($p = .037$, $d = 1.232$). There were significant effects of group [$F(1,25) = 7.664$, $p = .010$, $\eta^2 = .177$] and of time*group [$F(2,50) = 5.122$, $p = .009$, $\eta^2 = .040$] for RMSSD. Post hoc analyses report that AA profile has a lower RMSSD than NA profile. AA profile has a lower RMSSD than NA profile at baseline ($p = .004$, $d = -1.548$), before simulations compared to NA profile at baseline ($p = .017$, $d = 1.330$), and at the end of simulations compared to NA profile at baseline ($p = .014$, $d = 1.370$). Moreover, AA profile has a higher RMSSD at the end of simulations compared to baseline ($p = .036$, $d = .783$). There were significant effects of group [$F(1,25) = 8.190$, $p = .008$, $\eta^2 = .161$], and of time*group [$F(2,50) = 3.900$, $p = .027$, $\eta^2 = .043$] for pNN50. Post hoc analyses show that AA profile has a lower pNN50 than NA profile. For the time*group effect, AA has a lower pNN50 than NA at baseline ($p = .003$, $d = -1.533$), before simulations compared to NA profile at baseline (p = .007, d = 1.437), and at the end of simulations compared to NA profile at baseline (p = .007, d = 1.429). Moreover, NA profile has a lower pNN50 at the end of simulations compared to baseline (p = .044, d = .914).

In *frequency domain*, there was a significant effect of group [F(1,25) = 8.427, p = .008, η^2 = .204] for LF. AA profile has a lower LF than NA profile. There were significant effects of time*group [F(1,25) = 4.155, p = .021, η^2 = .039], and group [F(1,25) = 5.226, p = .031, η^2 = .122] for HF. Post hoc analyses report that AA profile has a lower HF than NA profile. For the time*group effect, AA profile has a lower HF than NA profile at baseline (p = .018, d = -1.340), before simulations compared to NA profile at baseline (p = .042, d = 1.198), at the end of simulations compared to NA at baseline (p = .042, d = 1.213). Moreover, NA profile has a lower HF at the end of simulations compared to baseline (p = .042, d = .832).

In *nonlinear domain*, there were significant effects of group [F(1,25) = 7.664, p = .010, η^2 = .177], and of time*group [F(1,25) = 4.155, p = .021, η^2 = .039] for SD1. Post hoc analyses reveal that AA profile has a lower SD1 than NA profile. For the time*group effect, AA profile has a lower SD1 than NA profile at baseline (p = .004, d = -1.548), before simulations compared to NA profile at baseline (p = .017, d = 1.330), at the end of simulations compared to NA profile at baseline (p = .014, d = 1.370). Moreover, NA profile has a lower SD1 at the end of simulations compared to baseline (p = .036, d = .782). There was a significant effect of group [F(1,25) = 6.450, p = .018, η^2 = .148] for SD2. AA profile has a lower SD2 than NA profile. There was a significant effect of group [F(1,25) = 9.343, p = .005, η^2 = .234] for α2. AA profile has a higher α2 than NA profile.

3.3. Impact of anticipatory anxiety profiles on perceived stress and cognitive load during CBRN simulations

The subjective stress and cognitive load of participants were measured after performing two and three simulations.

Subjective stress. Considering participants who completed two simulations, there was a significant effect of time*group [F(2,16) = , p = .039, η^2 = .151]. Post hoc analyses report that AA profile tends to perceive less subjective stress (p = .076, d = 1.568) at the end of the simulations compared to baseline. Considering those who performed three simulations, there was a significant effect of time*group [$F(3,45) = 3.268$, $p = .030$, $\eta^2 = .079$]. Post hoc analyses reveal that AA profile perceived more subjective stress at baseline compared to after two simulations ($p = .012$, $d = 1.337$), and compared to NA profile at the end of simulations ($p = .019$, $d = 1.804$).

Cognitive load. There was a significant effect of group [$F(1,15) = 6.260$, $p = .024$, $\eta^2 = .212$]. NA profile engaged in three simulations, has a higher cognitive load than AA profile.

3.4. Impact of anticipatory anxiety profiles on exteroceptive abilities after a CBRN simulation

Olfaction. For hedonic value, there was a significant effect of time*group [$F(1,24) = .013$, $p = .018$, $\eta^2 = .019$]. Post hoc analyses reveal that NA profile increased their hedonic value ($p = .004$, $d = -.581$) at the end of simulations compared to baseline.

Proprioception. Significant differences were found for open and closed eyes conditions. In the open eyes condition, there was a significant effect of group for the percentage of weight towards the right front [$F(1,16) = 5.987$, $p = .026$, $\eta^2 = .190$], and for the percentage of weight to the right rear [$F(1,16) = 5.368$, $p = .034$, $\eta^2 = .186$]. AA profile has a lower percentage of weight towards the right front, and a higher percentage of weight to the right rear compared to NA profile. In the closed-eyes condition, there was a significant effect of group for the percentage of weight towards the right front [$F(1,16) = 6.905$, $p = .018$, $\eta^2 = .219$], and the right rear [$F(1,16) = 7.146$, $p = .017$, $\eta^2 = .223$]. AA profile has a lower percentage of weight towards the right front and a higher percentage of weight towards the right rear compared to NA profile.

3.5. Anticipatory anxiety profiles on psychological recovery

Sleep. There was a significant effect [$F(1,22) = 4.421$, $p = .047$, $\eta^2 = .167$] on sleep demands. AA profile has a greater need for sleep the day after the end of the simulations than the NA profile.

Table 6 presents a summary of the psychophysiological and sensory differences after one week of CBRN training simulations.

4. Discussion

Understanding and addressing CBRN risk has wider implications due to the stress levels generated, the constant threat of unexpected, unpredictable, and uncontrollable circumstances and the high level of performance required.

Providing medical support in CBRN situations presents multiple challenges in terms of the complexity of medical care provided, as well as the significant stressors that medical personnel will face. First responders deployed on site are at risk of being exposed to an agent, either chemically [184, 185], radioactively [186–189] or due to the instability of the environment following the disaster [189]. Delivering effective training remains complicated due to time constraints, to the pedagogical and logistical challenges related to the simulation of the agents, and the scarcity of experts in the field since accidents rarely happen [14]. Thus, this study evaluates the impact of anticipatory anxiety among health professionals during simulated interventions involving victims in CBRN operations. Overall, results highlight contrastingpsychophysiological and sensorimotor functioning among profiles. The AA profile showed a reduced quality of physiological and sensorimotor adaptation in a constrained environment, while the NA profile contributes to a greater environmental response.

4.1. The impact of anticipatory anxiety on psychophysiological and sensory responses following CBRN simulations

4.1.1. Involvement of psychophysiological state in CBRN risk

The study of psychophysiological responses shows that the AA profile is more at risk than the NA profile. The AA profile perceived a lower level of stress at the end of simulations, regardless of the number of simulations performed. This result is similar to a study measuring psychophysiological responses in jumpers. They showed significant anticipatory anxiety before jumping, and a decreas after [139]. Nevertheless, the stress level of the AA profile is consistently higher than that of the NA profile. The AA profile is mostly composed of drivers compared to the NA profile, which is mostly doctors. Having served the longest with the BSPP and having the most professional experience as firefighters, drivers have the highest level of seniority and appear to be the most at risk in terms of burnout and exhaustion. Two studies have highlighted alarming results on burnout among emergency crews [190–194]. It should be noted that this is not a widely studied population, with the majority of experiments focusing on burnout in care teams [195–198]. This finding underlines the need for specific care where workload is a contributory factor in deviance towards burnout [190; 192]. Furthermore, simulation can in themselves be a profoundly stressful for the medical team (Müller et al., 2009). A study to assess the psychophysiological responses of soldiers during an operational maneuver both with, and without PPE gear, showed an increase in subjective stress levels and heart rate [46]. The authors to suggested an increase in the psychological load associated with PPE use.

Nevertheless, the NA profile has a higher cognitive load after three simulations. This result reflects a cumulative effect of environmental demand through greater resource allocation. Cognitive overload occurs when participants use working memory resources to engage in cognitive processes that are not essential to task performance. In order to optimize performance, cognitive load should always be kept to a minimum, but not so low as to induce boredom. Vytal and collaborators [200] have shown that anxiety alters working memory in situations of low mental load, and that an increase in cognitive overload is linked to a decrease in anticipatory anxiety. Thus, the mental load related to the demands of the task and the level of anxiety would be linked to performance. The question then arises: due to their anticipatory anxiety, would the AA profile have the capacity to engage in a task requiring significant resource allocation? Following this approach, they would also be more likely to make mistakes, not only because of their reduced cognitive capacity, but also because they would be more prone to burnout.

At the level of the cardiac biosignal, there is a decline in all HRV indices, in the time (i.e., SDNN, RMSSD, pNN50), frequency (i.e., LF, HF) and non-linear (i.e., SD1, SD2) domains of the AA profile compared with the NA profile. This result reflects a coactivation of the parasympathetic and sympathetic systems, demonstrating an inhibition of heart rate by the SNP, a function associated with high stress levels [99]. Nevertheless, the AA profile has a higher $\alpha 2$ than NA without exceeding 1.0, reflecting a complex, adaptative internal system [201, 202]. Therefore, although the level of perceived stress was lower than at the beginning of the internship week, it is nonetheless high which is also reflected in the post-simulation physiological response. Bong and collaborators [203] showed that simulation-based training activated doctors' physiological response, via an increase in cortisol levels. There has been a suggestion that when task demand is intense, there may be a decrease in HRV via coactivation of SNS and SNP [204]. Nonlinear HRV analysis appear to be relevant to a better understanding of adaptations of the system when meeting the constraints exerted on it by a task or the environment [205–207].

Previous studies have observed that if individuals proactively anticipate an emotional stimulus, lower cognitive effort is exerted when the stimulus occurs [208]. Importantly, trait and state emotion regulation and HRV are not independent of each other. A study shows that in challenging situations, individuals with an efficient emotion regulation abilities and high baseline HRV react with a further HRV increase, while those with a lower HRV react with a further HRV dampening [209]. Nasso and collaborators [100] studied adaptative and maladaptative anticipatory emotion regulation on the autonomous nervous system under constraint. They noted that anticipatory emotion regulation led to a higher stress response and was moderated by the level of rumination.

The NA profile shows generally more negative affect than the AA profile, and a weaker cardiac biosignal, notably through decreases in HRV (i.e., RR intervals), in SNP over time and frequency (i.e., pNN50, HF), and in the width of the ellipse of the Pointcaré plot (SD1), which reflects short-term variability. These results underline the fact that CBRN simulations degrade the body's physiological functioning. These results coincide with those of Visted et al. [210], who highlighted an association between negatively valenced emotions and the vagal component of HRV. They suggest that emotional regulation is associated with the modulation of physiological processes to meet environmental demand. Pollatos et al. [211] conducted a study to identify the brain structures activated during interoceptive awareness of heartbeats. They showed that specific brain structures such as the insula, the dorsal cingulate gyrus and the dorsomedial prefrontal cortex are all involved in processing of cardiac sensations. They suggested that negative emotions are linked to the dorsal cingulate gyrus and dorsomedial prefrontal cortex. These results are close to those of Strigo and Craig [212] that highlighted the role of the insular and cingulate cortex in the bilateral integration/modulation of cardiorespiratory and emotional signals. Moreover, it has been suggested that emotions and cognition share neural circuits that have an impact on decision-making and reasoning abilities [213]. Thus, negative emotions are associated with high cognitive load [214]. A study on simulation training of medical students showed that invigorating, stress-related emotions induced a perception of higher cognitive load [215]. Plass and Kalyuga [216] demonstrated a stress-induced increase in neural circuit load during learning which resulted in higher cognitive load and reduced performance. These results are in line with the model of Neurovisceral Integration which highlights an association between lower HRV and difficulties in accepting negative emotions due to reduced cortical inhibition of the amygdala [217, 218].

There enhanced awareness and, *in fine*, consideration of the environment may also reflect their engagement in the task. Studies on flow, represented by a psychological state in which individuals engaged in an activity find themselves [219], have highlighted a link between cognitive overload, activation of the ANS in its sympathetic and parasympathetic components and task difficulty [220, 221]. The experience of flow is linked to an increase in SNS [222], and a decrease in SNP [221, 222–225]. Although SNP inhibition is associated with cognitive overload, the role of SNP in flow is unclear [221].

After the simulations, the AA profile had a greater need for sleep than the NA profile, reflecting the need for greater recovery periods following increased physiological demands on the body. The AA profile would also have a greater vulnerability factor, to which simulations added a further negative effect. Sleep is a fundamental physiological need related to optimal functioning and health. Literature on extreme environments has shown that sleep is one of the most affected components [226–228]. Studies reported that sleep deprivation may result in performance and health impairment [229, 230], especially among health care workers [231–233]. Impacts may include an increase in the number of errors that may lead to an increase in the danger already present following a CBRN incident. Fatigue is associated with memory problems, increased anxiety and reduced problem-solving ability [234, 235].

4.1.2. Involvement of sensory information in CBRN risk

At the end of the simulations, the AA profile decreased in postural awareness. This result is linked to a lower weight distribution towards the right front, and a higher percentage of weight towards the right rear compared to the NA profile. Since posterior lean anticipates recoil, this result is not surprising in view of the anticipatory anxiety profiles identified. A study [236] demonstrated the opposite process by correcting posture with a biofeedback device to reduce stress. The body operates as a self-unit through interoceptive and exteroceptive pathways. Proprioception is both an inter- and exteroceptif signal [237, 238]. Our connection to the world is shaped by the interactions between the body and the environment [239].

Stress conceptualized through a bidirectional communication on the brain-body axis alters the internal representation of bodily processes [240, 241]. Brain structures underlying anticipatory anxiety are strongly related to the representation of the self and the world. Indeed, the activation of the anterior cingulate cortex and the insula are closely involved in interoception [240, 242, 243] and exteroception [211, 244–246]. Interoception is defined as the perception of the body's internal signals [212, 240, 247], allowing for the maintenance of the homeostatic balance of the body's internal state [245]. Thus, afferent signals (i.e., bottom-up pathways) would participate in the regulation of inferent signals (i.e., top-down pathways) of the physiological state of the body, through the central nervous system. Interoception is consequently a key element in understanding the relationship between the body and the brain. Several studies suggest a relationship between insular hyperactivity, interoception and anxiety [240, 248, 249], while others emphasize the role of the anterior cingulate cortex in anxiety [60, 72, 251, 251]. The brain contains intrinsic systems for processing exteroceptive sensory inputs (i.e., perception of the body in the environment) from the world. Nevertheless, few studies have shown a link between human interoceptive and exteroceptive abilities [211, 212, 252–254]. In a review, Berntson and Khalsa [245] highlighted the neural construct of interoception, notably the role of cortical and limbic regions. Understanding these cerebral structures shed light on interoceptive pathways and their association with the central nervous system and exteroceptive pathways.

Our results on proprioception impacts suggest that during anticipatory anxiety both exteroceptive and interoceptive signal processing seem to be impacted, contributing to damage to the body-brain balance needed to perform efficiently. Maintaining stable homeostasis may depend on both adequate perception of changes in the external world and the impacts that external changes have on interoception.

Two assumptions may be formulated concerning the improved odor hedonic value of the NA profile. First, the the end of the training week corresponds to the final measurements. Participants have successfully completed the simulations and are on their way to go home, which means returning to their families, and the environment of their daily lives. Secondly, a state of hypervigilance can also be generated during simulations and has already been defined within stress studies [255–258] and social isolation studies [259]. This state of hypervigilance is related not only to the specific characteristics of the environment, but also to the wearing of PPE clothing, which isolates participants from the outside world.

4.2. Countermeasures to facilitate quality adaptation in constrainted environments

The cost of the simulations appears to differ between the AA and NA profiles. The NA profile, although it reflects better functioning through greater situational awareness, has a modified psychophysiological response. The environmental constraints of accumulated simulations, combined with the stress factors they provoke, lead to cognitive overload of which the negative affects can diminish performance and lead to errors. At the same time, the physiological and sensory responses of the AA profile lead to increase their vulnerability post action and during recovery. It seems reasonable to assume that in an environment whose demands might exceed an individual's resources, withdrawal could become a coping strategy. As doctors represent the majority of the AA profile, their position means that they are more likely to adopt coping strategies based on emotional withdrawal. In addition to their specific role in a CBRN context, they have to find strategies to deal with work stress on a daily basis. The literature indicates that stressful and demanding professional environments induce barriers to compassionate care [260] and that withdrawal as a coping strategy is not effective over the long term [261, 262]. Furthermore, doctors may anticipate the challenges they will face. This might suggest that the NA profile is reactive rather than anticipatory, leading to a higher cognitive load. Nevertheless, since the AA profile is already involved in the task before being confronted with it, they would be more exhausted than the NA profile, as the task would have subjectively lasted longer.

The growing emergence of targeted countermeasures to improve the quality of individuals' adaptation is a favorable outcome to propose to medical teams alongside their training in CBRN risk. These countermeasures must be integrative and specific, i.e., based on both a physiological and cognitive approach. It is essential to be able to offer the possibility of reinforcing both the SNP and the perception of cognitive resources. This second option may be necessary in the case of our population. Several countermeasures have been studied in recent years. Cognitive therapies have shown encouraging results. These include mindfulness-based interventions for depression, stress, burnout prevention and quality of life [263–265]. Mindfulness is the awareness that emerges when paying conscious attention, in the present moment and non-judgmentally, to an unfolding experience [266, 267]. The mindful disposition has been associated with various positive aspects of physical and psychological health and protective functioning by maintaining attentional and cognitive flexibility capacities [263, 268, 269]. Resilience-based interventions have also shown promising results in proactively developing psychological skills. Resilience strengthens an individual's ability to move forward in the face of adversity or significant stress [270]. Studies have reported that resilience may help decrease depression and burnout and increase well-being [271–273] and has implication in preventing trauma during military deployment [274]. Also, interventions based on positive psychology show the effectiveness of inducing positive emotions and resilience [275, 276]. Positive psychology promotes high levels of mental health, well-being, quality of life and prevents pathologies [277]. Studies have shown its potential in promoting emotional regulation and reducing the risk of depression, anxiety and stress (275, 276, 278, 279, 280]. Thus, there are beneficial to training the psychological abilities of health professionals dealing with emergencies [281–284].

Moreover, noninvasive brain stimulations show promising results in improving ability to cope in constrained environment [285]. This technique modifies brain activity by sending impulse of transcranial electric fields using transcranial magnetic or electrical stimulation. The former may induce neuroplasticity [286, 287] and motor learning in surgery [288, 289] while the latter brought about an improvement in cognitive [290, 291], and motor performances [292, 293]. Nevertheless, the potential of these approaches is large by improving sleep quality [294, 295]. They may impact anticipatory anxiety individuals to promote recovery; symptomatology of psychological disorders

[296, 297]; alertness [298, 299]; working memory [300, 301]; decision making [302]. Noninvasive brain stimulation represents thus a strong potential complement to the interventions described above to consolidate motor learning while improving individual performance. In the event of a CBRN incident, medical teams are faced with the challenge of continuing to provide emergency care in dangerous conditions, with the added difficulty of wearing PPE. Consequently, they have to learn anew familiar medical procedures (e.g., intubation, perfusion) to suit unfamiliar circumstances.

Countermeasures also require further research into minimizing the negative effects of wearing PPE [303, 304]. Progress in the development of PPE wear aimed at reducing the psychophysiological cost to the body is essential. Providing the keys to facilitating the adaptation of first responders also involves improving external factors. These countermeasures would be applicable both as a preventive measure intended to increase individual resources and, on return from mission, as a means to limit decompensation, promote resilience and thus reduce the risk of developing an anxiety disorder, PTSD or burnout. Although pre- and post-traumatic factors are contributory to the development of PTSD [305], peri-traumatic factors and threat perception in particular play a crucial role [306–309]. A further preventive measure might be to develop a multimodal monitoring using both psychophysiological and cognitive data for predictive diagnostics among first responders [310]. Buller et al. [311] investigated the performance of an algorithm to estimate body temperature in first responders wearing PPE during three exercises. The algorithm was based on sequential heart rate measurements. Participants with the highest body temperature had an average heart rate of 140 bpm and a body temperature of around 39°C. The results showed that the algorithm was capable of estimating core temperature in different ambient environments. Used in conjunction with other real-time measurements, this type of tool is promising to identify the state of fatigue and decrease in performance in real time. It may also limit errors in decision making and the delivery of care as well as reduce the risk of maladaptation. Furthermore, monitoring enables individualized tracking of stress, an essential factor when we know that responses to multiple stressors differ widely from one individual to another.

Nevertheless, anxiety may decrease performance or enhance learning [312, 313]. So, there is a real interest in improving training and research. Determining the factors that come into play and the impact on actual risk are important and depend on the individual's degree of knowledge and experience. In combat situations, one study found that more experienced soldiers exhibited higher physiological response, decreased memory capacity and cognitive impairment [314]. Taken together, these findings reinforce the need to prepare individuals likely to be exposed to a CBRN disaster.

4.3. Training healthcare professionals in CBRN risk management

Results highlighted in this study underline the need for further training of medical teams in the event of a CBRN incident. The impact of CBRN risk training on stress response has not been sufficiently studied. Experience gained through training can significantly reduce the negative effects of stress on the psychophysiological response, particularly in anxious anticipators [315]. Emergency management is an integral part of a CBRN event. It requires a methodical and systematic approach to successfully counter the risk involved. The operational terrain is complex for first responders. It requires the management of fatalities, the triage of victims, the care of the most seriously injured, the management of the CBRN agent involved and therefore of the contamination/decontamination chain, and the supervision and protection of civilians beyond the red zone. Studies have shown that only 10% of responders understand the CBRN environment. Many do not know the principle of decontamination, nor the symptomology and relevant antidotes to the various CBRN agents, to which unequal attention is given during training (i.e., insufficient training for radionuclear events) [149, 152].

Training needs to be improved worldwide and greater conformity between institutions achived, in order to better prepare all those involved. This is especially important in light of a study showing that only 11.9% of those concerned had full situational awareness unrelated to their level of education [152]. One of the aims of developing the « I AM THOR » cognitive tool is to make it easier for first responders to learn the CBRN chain [16, 170]. This could be incorporated into training courses to facilitate the memorization of key actions in the event of a disaster, and thus reduce poor decision-making in the field. In 2015, the Japanese Disaster Medicine Association initiated a course on life support for first responders in the event of a CBRN incident without the need to identify the agent involved [316].

Simulations provide an insight into crisis management during a CBRN event, both into the technical skills (e.g., providing medical care) and the non-technical skills (e.g., communication skills, teamwork). A qualitative study conducted in China identified eight areas of non-technical skill in health response to CBRN disasters: (1) situational awareness, (2) communication skills, (3) collaboration, (4) resource management, (5) task management, (6) cultural competence, (7) austere environment skills, and (8) physical stamina [317].

To improve training for healthcare professionals in the event of a CBRN disaster, we therefore formulate several recommendations: increasing the number of training sessions in a year; regularly repeat simulations in real-life conditions; favoring short modules followed systematically by a simulation exercise; using scenarios that challenge responders by taking them to some extent out of their comfort zone; reinforcing knowledge of CBRN agents, identifying the links in the CBRN chain, apprehend waste management in a CBRN context; teaching the transversal skills to be acquired (i.e., technical and non-technical); learning how to wear PPE; consolidating cooperation and communication between teams and between institutions in the management of a CBRN incident (e.g., hospitals, police, army, rescue and emergency services); clearly defining the role of health professionals in disaster management; raising the awareness of the human and material resources that will help responders to survive in a stressful environment; systematizing debriefing sessions as one of the most important moments to consolidate learning; calling on the five principles of Crisis Resource Management (CRM) (i.e., role clarity, communication, mutual support, use of resources and situational awareness), and exploiting the potential of new technologies to provide simulations that are as close to reality as possible [152, ; 318–326]. Beyond these aspects, resource-building, social support and team cohesion also need to be considerated into long-term programs (i.e., from hardening to operationalizing teams).

Virtual Reality (VR) is being increasingly used in the training of healthcare professionals. This technology has the advantage of simulating individualized medical and situational crises of increasing complexity in real time. It can device complex, rare and diverse scenarios, and makes it possible to go back over past mistakes while creating an immersive environment from scratch adapted to the learner’s pathway. This reduces the amount of time medical teams have to allocate to training, and consequently allows for greater scheduling flexibility. It also enables instructors to monitor and observe individual performance as well as teamwork.

A matter of prime importance that has not yet been addressed is the identification of training needs. These depend not only on the level of prior training and experience, but also on the personality and resources of each individual. Studies have shown that identifying needs will improve the performance of individuals in the event of a CBRN disaster (i.e., victim triage, teamwork, communication, victim management and appropriate antidote depending on the agent used, following instructions, coordination between medical teams and institutions) [327–329]. This makes it a relevant tool for fostering learning.

Since inter-individual variations are important to deal with such an unexpected, unpredictable, and uncontrollable crisis, the way a professional cope with such a situation is dependent on several factors ranging from his resources to the environmental demand, and to the perception of his ability to deal with the unexpected, unpredictable, and uncontrollable crisis. This is particularly the case under the constraints of isolated, confined, extreme and unusual environments. Some professionals will be able to function optimally and recover effectively [330–341] while others will be more vulnerable and prone become less efficient during a mission [342–344]. Moreover, authors [345] report that guided imaginary training during spaceflight tasks decrease astronauts' stress. This information may be easily assimilated to emergency care training.

5. Limitations

This study has methodological shortcomings inherent to the ecological environment. The first limitation is the small sample size. This study was conducted as part of a CBRN training week that takes place three times a year. Given the simulation issues but also due to the primary training objective, only a small group of responders can participate. Second, psychophysiological, and sensory measurements were not taken during the simulations. Data collection occurred just after the debriefing of each simulation, limiting the observation of the state of functioning *in situ*. Third, it is difficult to differentiate in our analysis between the underlying factors related to wearing PPE suit and those inherent to the simulation exercises. Measurement of body temperature, for instance, was not included even though this leads to an increase in heart rate, especially when wearing PPE. Also, technical, and non-technical skills were not evaluated. These are important factors in the development of a participant's capacities and a study specifically aimed at evaluating the training will be conducted in the future. Fourth, clustering to differentiate our population according to an anticipatory anxiety profile might be disputed. One study suggests that ANS responses elicited by anticipation of a stressor may not be a reliable marker of anxiety [101]. This is still a sparse field of study to date. The implication of anticipatory anxiety with respect to perceived anxiety during a task is unclear and we may question whether these notions, and their neurophysiological pathway., are similar. The decrease in perceived subjective stress before and post simulations suggests that anticipatory anxiety is stronger than the level of anxiety actually felt at the time of the event. Fifth, psychological data (collected through questionnaires) are subjective measures. The use of intelligent sensors would provide more objective measures describing subjects' functioning and the processes involved when adapting to constrained environments.

6. Conclusion

This is one of the first investigations into of psychophysiological and sensory functioning in healthcare professionals during CBRN risk simulations. First responders have to maintain their performance at the highest level to be able to respond to the strictures of their environment and to keep both themselves and any victims alive. Anticipatory anxiety is one of the gateways to understanding its influence on psychophysiological and sensory responses in a stressful environment. This study highlights vulnerability in the anticipatory anxiety profile in relation to burnout. Understanding an individual's responses to a high-demand environment and providing appropriate training is fundamental to ensuring efficient performance and care. It is consequently vital that the exploration of countermeasures that promote adaptative behaviors should continue since they may influence the outcome of an accident. When life is hanging by a thread, only an individual's ability to cope with his or her environment will help amidst the chaos.

7. References

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8. Supplementary Material

Additional file 1

Bayesian analyses for differences among profiles at baseline.

Interoception. None of the other interoceptive measures between profiles reach the significance: noticing (p = .435, BF_{10} = .454), not distracting (p = .879, BF_{10} = .363), not worrying (p = .087, BF_{10} = .889), attention regulation (p = .124, BF_{10} = .902), emotional awareness (p = .745, BF_{10} = .374), self-regulation (p = .221, BF_{10} = .640), body listening (p = .469, BF_{10} = .439), trusting (p = .555, BF_{10} = .411) at baseline.

Mindful disposition. None the presence (p = .591, BF_{10} = .401), and acceptation (p = .680, BF_{10} = .384) did change between profiles at baseline.

Coping flexibility. None of the appraisal (p = .143, BF_{10} = .827), and adaptative (p = .304, BF_{10} = .540) coping did change between profiles at baseline.

Emotion. None the negative (p = .137, BF_{10} = .847), and the positive affect (p = .526, BF_{10} = .419) did change between profile at baseline.

Body posture awareness. None the ease and familiarity with postural awareness (p = .437, BF_{10} = .460), and the attention regulation's need (p = .178, BF_{10} = .735) between profile reach the significance at baseline.

HRV. None the LF/HF ratio (p = .259, BF_{10} = .588), α1 (p = .505, BF_{10} = .426), and sample entropy (p = .801, BF_{10} = .368) change between profiles at baseline.

Olfaction. None the detection (p = .975, BF_{10} = .364), identification (p = .938, BF_{10} = .503), and hedonic value (p = .883, BF_{10} = .366) of the odor between profiles at baseline reach the significance.

Proprioception. In open-eyes condition, the percentage of weight towards the front left (p = .590, BF_{10} = .459), the percentage of weight to the left rear (p = .740, BF_{10} = .430) did not change between profiles at baseline as well as in closed-eyes condition for the percentage of weight towards the front left (p = .325, BF_{10} = .587), and the percentage of weight to the left rear (p = .351, BF_{10} = .566).

Bayesian analyses for impact of CBRN training simulations among profiles.

Emotion regulation. None the positive affect for time (p = .673, BF_{10} = .300), time*group (p = .457, BF_{10} = .187), group (p = .304, BF_{10} = .624) change between profiles after the simulations.

Subjective stress. None of the subjective stress for time (p = .175, BF_{10} = .571), group (p = 1.000, BF_{10} = .477) concerning participants that completed two simulations did change. None of the subjective stress for time (p =.059, BF_{10} = .326) and group (p = .116, BF_{10} = .195) did change concerning participants that took part at three simulations.

Cognitive load. None of the mental workload for time (p = .598, BF_{10} = .444), time*group (p = .915, BF_{10} = .379), group (p = 521, BF_{10} = .857) concerning participants that completed two simulations did change. None of the mental workload for time (p = .688, BF_{10} = .078), and time*groups (p = .480, BF_{10} = .234) did change concerning participants that took part at three simulations.

Body posture awareness. None the ease and familiarity with postural awareness for time (p = .048, BF_{10} = 1.000) and group (p = .957, BF_{10} = .467); the attention regulation's need for time (p = .371, BF_{10} = .311), time*group (p = .401, BF_{10} = .241), group (p = .227, BF_{10} = .755) did change.

Sleep. None the physical shape (p = .085, BF_{10} = .581), mental health (p = .387, BF_{10} = .491); and mood (p = .243, BF_{10} = .621) change after the simulations.

HRV. None the RR intervals between groups (p = .461, BF_{10} = .019); SDNN for time (p = .319, BF_{10} = .045); RMSSD for time (p = .181, BF_{10} = .040); pNN50 for time (p = .096, BF_{10} = .065); LF for time (p = .913, BF_{10} = .019), time*group (p = .871, BF_{10} = .120); HF for time (p = .133, BF_{10} = .129); LF/HF ratio for time (p = .264, BF_{10} = .227), time*group (p = .183, BF_{10} = .219), group (p = .101, BF_{10} = 1.000); SD1 for time (p = .181, BF_{10} = .038); SD2 for time (p = .302, BF_{10} = .069), time*group (p = .108, BF_{10} = .249); SD ratio for time (p = .209, BF_{10} = .280), time*group (p = .162, BF_{10} = .223), group (p = .161, BF_{10} = 753); α1 for time*group (p = .238, BF_{10} = .424), group (p = .832, BF_{10} = 077); α2 for time*group (p = .257, BF_{10} = 1.000); sample entropy for time (p = .410, BF_{10} = .191), time*group (p = .493, BF_{10} = .100), group (p = .739, BF_{10} = .508) did change.

Olfaction. None the detection for time*group (p = .251, BF_{10} = .462), group (p = .540, BF_{10} = .168); the identification for time (p = .210, BF_{10} = .564), time*group (p = .576, BF_{10} = .340), group (p = .662, BF_{10} = .586), and hedonic value between groups (p = .392, BF_{10} = .089) of the odor change between profiles after the simulations.

Proprioception. None the percentage of weight towards the right front for time (p = .222, BF_{10} = .275), time*group (p = .808, BF_{10} = .676); percentage of weight towards the front left for time (p = .210, BF_{10} = .616), time*group (p = .763, BF_{10} = .347), group (p = .505, BF_{10} = .558); percentage of weight to the right rear for time*group (p = .781, BF_{10} = 1.000); percentage of weight to the left rear for time (p = .281, BF_{10} = .518), time*group (p = .889, BF_{10} = .265), group (p = .680, BF_{10} = .500) in open eyes condition as well as the percentage of weight towards the right front for time*group (p = .883, BF_{10} = 1.000); percentage of weight towards the front left for time*group (p = .618, BF_{10} = .581), group (p = .473, BF_{10} = .242); percentage of weight to the right rear for time*group (p = .928, BF_{10} = 1.000); percentage of weight to the left rear for time*group (p = .647, BF_{10} = .561), group (p = .493, BF_{10} = .231) in closed eyes condition did change.

Additional file 1

Table 6

Summary of the psychophysiological impact of CBRN training and recovery among profiles

	Baseline		*Pre-simulation*		*Mid 2 simulations*		*Mid 3 simulations*		*Post-simulation*		*Recovery*		*p*-value*
	AA	NA	AA	NA	AA	NA	AA	NA	AA	NA	AA	NA	
Emotion													
Negative affect	1.689 ± .577	2.014 ± .505							1.522 ± .361	1.944 ± .410			**.040**
Positive affect	4.089 ± .487	4.194 ± .324							3.989 ± .602	4.222 ± .372			.304
Anxiety													
State_all simulations	52.800 ± 1.781	48.667 ± 1.723							49.400 ± 5.193	47.667 ± 4.355			**.006**
State_2 simulations	52.400 ± 1.517	48.400 ± 1.673			48.000 ± 4.528	48.400 ± 3.912			46.200 ± 4.550	49.800 ± 5.675			1.000
State_3 simulations	53.000 ± 1.944	48.857 ± 1.864			47.918 ± 5.558	48.714 ± 2.215	49.223 ± 4.243	48.286 ± 3.729	51.000 ± 4.922	46.143 ± 2.610			.116
Cognitive load													
Mental workload_2 simulations					12.600 ± 2.790	11.300 ± 3.369			12.800 ± 3.392	11.433 ± 3.122			.521
Mental workload_3 simulations					11.333 ± 2.537	13.143 ± 3.563	10.033 ± 1.972	13.429 ± 2.706	10.867 ± 2.520	13.524 ± 2.465			**.024**
Body posture awareness													
Ease & familiarity with postural awareness	23.467 ± 6.791	21.182 ± 7.922							20.927 ± 8.038	20.927 ± 8.038	21.733 ± 8.319	23.091 ± 7.867	.957
Need for attention regulation	23.667 ± 7.037	19.949 ± 6.313							21.867 ± 7.530	20.000 ± 7.655	24.133 ± 6.696	20.091 ± 6.395	.227
Sleep													
Sleep demand											7.692 ± 1.756	6.173 ± 1.774	.047
Physic shape											7.982 ± 1.576	7.000 ± 1.000	.085
Mental health													

Mood							8.693 ± 1.369	9.391 ± 1.543	.243
HRV									
RR intervals	901.317 ± 128.163	1027.481 ± 143.907	903.628 ± 111.199	891.857 ± 889.502	889.502 ± 113.059	871.038 ± 152.266			.461
SDNN	57.393 ± 27.389	94.453 ± 23.256	67.633 ± 31.227	85.453 ± 26.181	61.604 ± 21.198	78.055 ± 29.150			**.011**
RMSSD	35.165 ± 18.692	72.675 ± 25.759	40.457 ± 20.133	56.120 ± 29.373	39.476 ± 22.053	53.718 ± 29.926			**.010**
pNN50	17.566 ± 18.016	47.854 ± 17.691	19.462 ± 17.859	31.583 ± 22.655	19.612 ± 19.698	29.795 ± 22.856			**.008**
LF	1532.016 ± 1597.875	4680.727 ± 3360.997	1987.256 ± 2415.085	4627.575 ± 3557.624	1724/836 ± 1163.810	4603.072 ± 4781.115			**.008**
HF	528.472 ± 657.955	1961.668 ± 1650.988	679.921 ± 563.042	1238.388 ± 1404.056	664.102 ± 721.797	1071.775 ± 1218.578			**.031**
LF/HF ratio	3.923 ± 3.448	6.525 ± 7.854	3.592 ± 2.186	8.653 ± 9.943	4.115 ± 3.249	8.339 ± 8.815			.101
SD1	24.864 ± 13.217	51.388 ± 18.214	28.606 ± 14.236	39.682 ± 20.770	27.913 ± 15.594	37.984 ± 21.161			**.010**
SD2	76.781 ± 37.116	122.376 ± 30.669	90.651 ± 42.270	112.870 ± 34.956	81.861 ± 27.285	102.168 ± 39.090			**.018**
SD ratio	3.381 ± 1.021	2.540 ± .757	3.380 ± .882	3.214 ± .976	3.307 ± .918	3.078 ± 1.007			.161
α1	1.102 ± .278	1.018 ± .368	1.155 ± 268	1.245 ± .316	1.207 ± .232	1.264 ± .352			.832
α2	.857 ± .239	.633 ± .237	.965 ± .249	.627 ± .299	.846 ± .222	.576 ± .291			**.005**
Sample entropy	1.306 ± .275	1.337 ± .364	1.300 ± .338	1.209 ± .360	1.297 ± .323	1.232 ± .468			.739
Olfaction									
Detection	15.429 ± .938	15.417 ± .996			15.643 ± .842	16.000 ± .000			.540
Identification	13.357 ± 1.499	13.167 ± 2.480			13.786 ± 1.718	13.333 ± 2.015			.662
Hedonic value	59.286 ± 12.869	60.000 ± 11.426			59.714 ± 14.274	67.167 ± 9.806			.392
Proprioception									
% of weight towards the right front (OE)	43.875 ± 9.583	55.700 ± 7.499			40.500 ± 15.372	50.700 ± 13.425			**.026**
% of weight towards the front left (OE)	50.000 ± 12.189	53.000 ± 10.944			45.000 ± 15.269	49.900 ± 16.265			.505
% of weight to the right rear (OE)	55.000 ± 10.850	44.300 ± 7.499			61.750 ± 16.714	49.300 ± 13.425			**.034**
% of weight to the left rear (OE)	48.875 ± 12.597	47.000 ± 10.944			52.750 ± 12.464	50.000 ± 16.323			.680

% of weight towards the right front (CE)	46.125 ± 8.626	57.800 ± 7.495		37.625 ± 16.195	50.100 ± 11.387		**.018**
% of weight towards the front left (CE)	51.250 ± 9.347	56.400 ± 11.626		46.625 ± 11.819	49.100 ± 14.918		.473
% of weight to the right rear (CE)	53.875 ± 8.626	41.900 ± 7.520		62.375 ± 16.195	49.900 ± 11.387		**.017**
% of weight to the left rear (OE)	48.750 ± 9.347	43.900 ± 11.561		53.375 ± 11.819	50.900 ± 14.918		.493

**p*-value used in the analysis of effects. Means and standard deviation are show for each variable. All variables were recorded before, during and after one week CBRN training. Open eyes condition (OE) and Closed eyes condition (CE).

Synthèse des résultats principaux

L'étude ANTIDOTE avait pour objectifs : (1) investiguer l'impact de l'anxiété anticipatrice chez des experts devant gérer une situation problème simulée en ambiance CBRN, l'impact étant étudié sur le plan des fonctionnements psychologiques, physiologiques et sensorielles ; et (2) étudier l'impact de cette anxiété anticipatrice sur la récupération ; la récupération cible le lendemain des simulations en se focalisant particulièrement sur la conscience corporelle et la fatigue. Nos résultats montrent que l'anxiété anticipatrice dans ce contexte est délétère pour le fonctionnement de l'individu. Elle impacte les réponses psychologiques, physiologiques et sensorimotrices et la récupération. Au lendemain des simulations en PPE, on observe un état de fatigue subjective associée à un besoin de sommeil accru. Il en résulte la nécessité fondamentale d'entraîner efficacement les équipes médicales pour assurer un niveau efficient de performance et de soin. Ces résultats suggèrent que l'anxiété anticipatrice doit être prise en compte pour optimiser le travail des premières équipes de terrain actives au décours d'un incident CBRN. La formation doit maintenir leur performance au plus haut niveau afin d'être en mesure de répondre à la sollicitation environnementale mais aussi de maintenir les professionnels de santé et les victimes en vie. Transposés à l'environnement spatiale, ces résultats soulignent l'enjeu de prendre en compte l'anxiété anticipatrice des astronautes pour leur donner des outils de gestion afin de réaliser au mieux leur mission et de gérer au mieux la situation critique.

Une autre situation à haut risque est le cas de la survie en mer. Survivre en mer est l'une des situations de survie les plus complexes, notamment parce que l'eau représente une des plus grandes menaces pour l'organisme. Si ce milieu est inapproprié pour la survie de l'espèce humaine, la survie en mer est surtout caractérisée par une forte incertitude quant à la fin de la situation critique. Elle oblige l'individu à gérer son stress dans un groupe stressé. Lors des LDSE, les équipages pourraient avoir à faire face à des situations qui les mettront en situation de survie. Ils seront alors livrés à eux-mêmes, en fonction de la « zone » spatiale dans laquelle ils se situeront. Nous n'avons pas le recul nécessaire aujourd'hui avec les missions à bord de l'ISS et les missions Apollo pour envisager ce type d'incident. Pour autant, le risque encouru sera réel et doit ainsi être envisagé et appréhendé. La littérature scientifique spatiale rapporte de nombreuses études impliquant un ensemble de challenges auxquels les individus doivent faire face. Toutefois, il est difficile de comprendre les mécanismes psychologiques, physiologiques, cognitifs et extéroceptifs en jeu dans l'adaptation, et les moyens par lesquels les ressources mobilisées peuvent être diminuées en situation de laboratoire. Il n'est par ailleurs pas éthique de générer des situations de survie réelles. Aussi, les exercices de survie en mer mis en place par les marins de l'École nationale supérieure maritime et ouverts à un public non professionnel offrent des conditions pertinentes pour répondre à l'objectif.

La seconde étude portant sur les situations critiques, étude RAD'LÔ, avait deux objectifs principaux : (1) évaluer l'impact d'une simulation de survie en mer sur les réponses psychologiques, cognitives, physiologiques et sensorielles ; et (2) mesurer la récupération dans les jours suivants la situation de survie.

Dans ce cadre de survie d'un équipage en mer, nous posons l'hypothèse que le contexte extrême de la survie en mer induit un impact majeur sur l'organisme, avec une récupération sur plusieurs jours.

Lost at Sea:

Impact of an Ocean Survival Experience on Psychological, Physiological, and Cognitive Abilities (RAD'LÔ)

En revision[9]

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Abstract

Introduction. Survival in an extreme environment places high physiological and cognitive demands on the individual. These environments are characterized by specific stimuli, including unusual sensory stimulation and uncertainty, which induce intense stress. Thus, the aims of this study are: i) to evaluate the impact of a five-day survival at sea simulation on human adaptive capacities, based on the assessment of psychological, cognitive, physiological, and sensorial measures; and ii) to assess recovery.

Method. Twenty-one healthy participants were enrolled in a 5-day simulation onboard a lifeboat or an inflatable raft. Psychological, physiological, sensory, and cognitive measurements were recorded before leaving (baseline), at the end of the experiment (post) and during the week that followed (recovery).

Results. Our results are unequivocal. The harshness of the environment affected the majority of the organism's responses. On the cognitive level, performance significantly deteriorated. On the psychological level, there was low mood, a decrease in subjective exteroceptive acuity and sleep disorders, increased energy, and less perceived stress. On the physiological level, a decline was recorded with respect to autonomous nervous system measurements. On the sensory level, we observed a state of hypervigilance and hypersensitivity to stimuli from the external environment. Proprioception was deeply impacted. Moreover, at recovery, many individuals did not fully recover or deteriorated further, especially regarding sleep, interoceptive abilities and sensory distortion. It appears that participants entered a state of psychological hibernation, associated with increased physical and cognitive load, and sensory hypervigilance.

Conclusion. These results raise the question of the risks that may be incurred during future long-term space missions, as astronauts will have to maintain their cognitive performance at a high level to be able to respond to environmental demands and remain alive. It is essential to continue to explore countermeasures that will support adaptation in future spacecraft crew.

Figure 19
Graphical abstract RAD'LÔ

Keywords

Adaptation, Cognition, Extreme and unusual environment, Health, Neurosciences, Sea survival, Stress

1. Introduction

Stories have been told about exploring the high seas since the dawn of time, and the misadventures of sailors are the subject of legends that have travelled through the ages. From Poseidon, God of the Sea, to the expedition led by Ernest Shackleton, history tells us that sailors can overcome the greatest of challenges: surviving a shipwreck in some of the most extreme environments on the planet. Both storybooks and the scientific literature record the life-threatening consequences for crews: death by hypothermia and/ or dehydration, drowning, or psychological collapse. They also tell us how a human being is able to survive in these environments. Current knowledge about survival at sea highlights several challenges for survivors: notably maintaining homeostasis, and the importance of their physiological, cognitive, and psychological coping skills.

These scenarios provide an ideal environment to study stressors in space. Isolation and confinement will be exacerbated by longer missions (e.g., to Mars), as will the risk of a life-threatening accident, especially if an incident occurs between two space bases. Other stressors include temperature variation that will challenge the individual's thermoregulatory capacities, and a significant lack of sleep, with repercussions for affect and decision-making (NASA, 2015; 2019). Future space crews will be entirely autonomous, unable to call for help in the case of difficulties, and their survival will lie in their own hands.

In this context, Isolated and Confined Environments (ICE) and Extreme and Unusual Environments (EUE) on Earth reflect conditions that can strain the physiological (e.g., thermoregulation, sensory deprivation), psychological (e.g., isolation, confinement, sleep deprivation) and cognitive (e.g., mental load) resources of the individual. They are characterized by specific environmental stimuli, including unusual sensory stimulation, uncertainty that creates intense stress, and the need for optimal cognitive and behavioral performance. While astronauts receive specific training to cope with these constraints, ICE and EUE are found elsewhere on Earth in the form of shipwrecks, space simulations, polar wintering, nuclear-powered ballistic missile submarines (SSBN), and external military operations.

1.1. The body’s response to stress

Being exposed to stress is known to have a profound impact on an individual, both psychologically and physiologically (Selye, 1956). Its occurrence activates two systems: the autonomic nervous system (ANS) (activation of the medullary centers), and the hypothalamic–pituitary–adrenal axis (cortisol release) (Chrousos, 1992; McEwen, 2007). It should be noted that a stressful experience will not necessarily be equally stressful for another individual. It is internal to each person, and is a function of available resources (e.g., personal experience, beliefs, skills, motivation, physical and mental conditioning, training, and self-confidence) (Cox, 1985; Harris, 1995; Hughes, 2012; Lazarus & Folkman, 1984; Maxwell & Roxborough, 1985; Ursin, 1988). Stress only occurs when the environmental demand exceeds the resources available to an individual to cope with it (Cox & Mackay, 1985; Lazarus, 1966, 1984). In this case, the body is unable to maintain its functioning at pre-set levels, in other words, the homeostatic balance.

Stress regulation mechanisms act on the body’s internal environment (Cannon, 1935), in particular, its fluid matrix. One indicator that is used to evaluate ANS activity is heart rate variability (HRV) (Kim et al., 2018a; Laborde et al., 2017; Sztajzel, 2004). Sympathetic and parasympathetic influences are evaluated by variation in the interval between successive heartbeats (i.e., RR interval) (Berntson et al., 1994; Rompelman et al., 1980). In general, vagally-mediated HRV is indexed by time domain measures, such as the root mean square of successive differences (RMSSD), and frequency domain measures such as high-frequency (HF) HRV (Thayer & Lane, 2000, 2009). Higher resting HRV is thought to indicate greater activity in the parasympathetic component, and conversely. HRV is also sensitive to psychological stress, with a fall indicating greater stress (Kim et al., 2018a). Rompelman et al. (1980) found clear indications of differences in the neural cardiovascular control of HRV among healthy subjects in different psychological states, and it has been shown to decrease with increasing mental load. Stress can therefore be conceptualized as bottom-up information, which acts bidirectionally on the brain-body axis, and alters the individual’s internal representation of their bodily processes (Craig, 2002; Hitchen et al., 1980; Schulz & Vögele, 2015).

1.2. Neural mechanisms underlying the representation of the world

Our connection to the world is shaped by interactions between our body and the environment (Varela et al., 1993). Initially defined by Sherrington (1906) as the ability to detect signals from the viscera (i.e., the internal environment), *interoception* is defined as the perception of the body's internal signals (Craig, 2002, 2009, 2014; Pollatos et al., 2007), which supports homeostasis (Berntson & Khalsa, 2021). Thus, afferent signals (bottom-up pathways) contribute to the regulation of inferent signals (top-down pathways) that control the physiological state of the body, through the central nervous system. Therefore, interoception is a key element in understanding the relationship between the body and the brain. Our understanding of interoception is rapidly expanding, and it is considered as the missing brick in many psycho-physiological mechanisms related to the neurotypical and pathological functioning of the organism.

In this context, Pollatos et al. (2007) identified the brain structures activated during interoceptive awareness of heartbeats. The study showed that specific brain structures such as the insula, the dorsal cingulate gyrus, and the dorsomedial prefrontal cortex are involved in the processing of cardiac sensations. Moreover, the authors suggested that negative emotions are linked to the dorsal cingulate gyrus, and the dorsomedial prefrontal cortex. The latter results are similar to those reported in Strigo and Craig (2016), who highlight the role of the insular and the cingulate cortex in the bilateral integration/ modulation of cardiorespiratory and emotional signals. Furthermore, in a review, Schultz and Vögele (2015) emphasized the association between interoception and stress, via the bidirectional transmission of information along the brain-body axis.

The brain contains intrinsic systems for processing exteroceptive sensory inputs from the world, such as vision, audition, olfaction, taste, and proprioception (Sepulcre et al., 2012). *Exteroception* is thus defined as bodily perceptions in a given environment. Studies of sensory deprivation have consistently highlighted a corpus of symptoms that include: difficulties in reasoning; visual and auditory hallucinations; generalized anxiety and depression; altered mood and psychosis; suicidal ideas; a feeling of apathy and lethargy; temporal distortions; cognitive disorders; disillusionment; and depersonalization that weakens the borders of reality (Anderson, 2004; Haney & Lynch, 1997; Leach, 2016; Leiderman, 1962; Moscovici & Doms, 1982; Scott & Gendreau, 1969; Solomon & Kleeman, 1971; Vernin & McGill, 1957). Furthermore, tolerance has been found to be relatively low in neurotypical individuals (Heron et al., 1956; Lilly, 1956).

A few studies have shown a link between human interoceptive and exteroceptive abilities (Harshaw, 2015; Moseley et al., 2008; Pollatos et al., 2007; Tsakiris et al., 2011. For example, Kleckner et al. (2017) identified the anatomical and functional substrates that provide cortical control lying between visceromotor regions (i.e., the dorsal anterior cingulate cortex, the pregenual anterior cingulate cortex, the subgenual anterior cingulate cortex, the ventral anterior insula, the dorsal amygdala), and the interoceptive cortex (i.e., the dorsal mid insula, the dorsal posterior insula). In a review, Berntson and Khalsa (2021) highlighted the neural constructs of interoception, notably the roles of cortical and limbic regions (i.e., the amygdala, the basal ganglia, the circumventricular organs, the dorsal motor nucleus, the hippocampus, the hypothalamus, the pituitary, the insular cortex, the medial prefrontal cortex, the nucleus ambiguous, the nucleus tractus solitarius, the orbitofrontal cortex, the periaqueductal gray matter, the parabrachial nucleus, the rostral ventrolateral medulla, the somatosensory cortex, and the ventromedial prefrontal cortex). The investigation of these cerebral structures sheds light on interoceptive pathways, and their association with the central nervous system and exteroceptive pathways.

The above observations suggest that maintaining homeostasis depends on both the correct perception of changes in the external world, and the correct perception of the impacts that these external changes have on interoception. Both interoceptive and exteroceptive signal processing may be impaired in a stressful environment, harming the body-brain balance.

1.3. Adaptation in an ICE/EUE environment

Adaptation has been defined as the ability of a person to change or adjust in response to changing conditions or situations (VandenBos, 2007). NASA has identified it as one of the five components to consider for future long-distance space travel (Landon et al., 2016). Bartone et al. (1998) identified five adaptation dimensions that have a significant impact on performance variability: (1) the degree of isolation, (2) ambiguity about the mission, (3) the degree of powerlessness, (4) feelings of boredom, and (5) the degree of danger and threat.

Exposure to an ICE/EUE environment weakens the homeostatic balance, and may induce psychological (depressive symptoms, anxiety, fatigue, mental disorders, confusion, mood disorders) (Bartone et al., 1998; Basner et al., 2014; Hunderson, 1968; Kanas, 1985, 1987; Kanas et al., 2013; Oluwafemi et al., 2021; Palinkas & Suedfeld, 2008; Palinkas & Suedfeld, 2021; Suedfeld & Weiss, 2000; Van Ombergen et al., 2021; Vasterling et al., 2006), physiological (modification of the cardiac biosignal, and electroencephalogram bands) (Demontis et al., 2017; Ferrara et al., 2013; Hughson et al., 2018; Moraes et al., 2020; Patel, 2020; Šolcová et al., 2014; Vigo et al., 2013; Wan et al., 2011; Bersenev et al., 2013) and cognitive (logical reasoning, learning, memory, vigilance, spatial processing, and reaction time) disorders (Cannon, 1929; Garrett-Bakelman et al., 2019; Harris et al., 2005a; Harris et al., 2005b; Lieberman et al., 2006; Lowe et al., 2007; Manzey & Lorenz, 1998; Marazziti et al., 2021; Morgan et al., 2006; Pagel & Choukèr, 2016; Strangman et al., 2014). In the context of military training, Lieberman et al. (2005) found that both Navy SEALS and Army Rangers showed a decline in low-level (reaction time, vigilance) and high-level (learning, memory, logical reasoning) cognitive functions, along with a fall in vigor and an increase in fatigue, depression, anger, and confusion.

However, the available data on the impact of extreme environments on cognition are heterogeneous, and mechanisms remain poorly understood. The decline in cognitive performance does not appear to be uniform over time (Manzey & Lorenz, 1998), and findings are inconclusive (Barkaszi et al., 2016; Folgueira et al., 2019; Gríofa et al., 2011; Kanas et al., 2013; Pilcher et al., 2002; Schneider et al., 2012; Strangman et al., 2014). For example, Marrao et al. (2005) examined exposure to cold during a 9-day survival course found no change in cognitive performance. On the other hand, cognitive performance appears to be closely related to sleep disturbance. Studies have reported poorer memory performance and an increase in attention problems when sleep is limited to between three and six hours (Van Dongen et al., 2003), and degraded executive functions, language and communication disorders, and poorer working and episodic memory after 16 hours of sleep deprivation (Durmer & Dinges, 2005; Harrison & Horne, 2000). These effects increase as deprivation increases, with a minimum of 13 hours of sleep required to recover (Leach, 1994). A pre–post comparison of a space mission found that sleep deprivation had the greatest effect on astronauts' reaction times (French et al., 1999). In a review, Lowe et al. (2007) highlighted that change in reaction times could be an early indicator of cognitive impairment, with a positive correlation between the two measures. The latter authors noted that cognitive impairment was observed after only five days of sleep deprivation, but that there was a disparity between the cognitive domains assessed.

It should be noted that these changes are not uniform and may vary considerably from one individual to another. Furthermore, the psychological, physical, and cognitive impacts of EUEs are relatively unknown, as most studies focus on ICE. In general, the literature shows that there is a need for an indicator to assess cognitive impairment in relation to a stressful situation, both ICE and/or EUE. This indicator would give an insight into the cognitive adaptation of the subject to the stressful situation.

1.4. Survival at sea

Survival at sea is considered one of the most complex survival situations (Filed manual, 1992), and it is associated with intense stress (Motley, 2005; Sarinas & Tagulalap, 2017S). Some stressors are specific to the environment (cold, workload, equipment, mission duration, security systems, previous experience, weather conditions, separation from loved ones, privacy, mental workload) (Sarinas & Tagulalap, 2017; Solberg et al., 2017). Water is the greatest hazard, and appropriate equipment is essential to sustaining life (Transport Canada, 2003). The environment requires the individual to work hard to stay alive, and the person must draw upon both cognitive and sensorimotor capacities (Haward et al., 2000; Petrie, 2007; Wertheim, 1998).

Some authors have studied the challenges of survival at sea, which include hunger, sickness, cold, discomfort, inability to sleep, lack of personal space, the desire to escape, cardiovascular changes, stress, hypothermia, and cognitive performance (Padron et al., 2015; Petrie, 2007; Rataj et al., 2017). Solberg (2017) emphasizes that preventing fatigue (via motivation) and the maintenance of cognitive performance are key elements in coping with a survival situation. The latter author examined a period of five days, with different craft (a lifeboat vs. a life raft), and the study highlighted an increase in the cardiac biosignal, which could reflect the degree of discomfort in the environment but could also reflect differences in activity in the two boats (i.e., less activity in the life raft). Increased activity could also be associated with other mechanisms, such as seasickness and energy level. Finally, from a cognitive point of view, Lowe and Reves (1999, 2000, 2002) reported a decrease in reaction time and poorer memory in divers, independent of both water temperature and working conditions.

1.5. Context of the experiment

Living in an ICE/EUE is a challenging endeavor. It is reasonable to ask what happens when an individual, who has been selected and trained to cope with the various stressors inherent to these environments, becomes someone who is unable to mobilize his or her resources, and is thus no longer able to survive. The intrinsically integrative nature of the psycho-physio-cognitive mechanisms involved in adaptation to environmental challenges makes them difficult to understand in their entirety. In addition to significant inter-individual variation, it is also difficult to determine the underlying mechanisms that lead to adaptation. Nevertheless, understanding these mechanisms is fundamental to: (1) reducing mission risk; (2) improving *in situ* and post-mission health; and (3) preparing individuals for an accident that threatens their survival.

Our study addresses the latter points. It examines a simulated situation where sailors must survive for several days at sea following damage to their boat. The objectives are twofold: (1) to evaluate the impact of a sea survival simulation on human adaptive capacities, based on the assessment of psychological, cognitive, physiological, and sensorial impacts; and (2) to assess recovery following time spent in this extreme environment.

2. Materials & Methods

2.1. Design

The present study (ID-RCB: 2017-A01329-44) was approved by the Committee for the Protection of Individuals (CPP Sud-Est VI, Clermont-Ferrand, France) and was conducted according to the standards of the Declaration of Helsinki. After comprehensive verbal and written presentations, all participants gave their written consent to participate.

2.2. Participants

Participants were healthy marines from the French Maritime Academy (*n* = 15), firefighters from the Marseille Naval Fire Battalion (*n* = 2), and volunteers from the Camondo Design School (*n* = 5). Their health status was confirmed by a clinical history and examination. One participant (from the Camondo School) was excluded for medical reasons, leaving 21 subjects (seven women and 14 men, *Mage* = 22 ± 6.3 years, ranging from 18 to 41). Among the seven women, two (28.57%) were using contraception (the pill, or a copper intrauterine device). None of the participants were taking medication. Three (14.28%) were smokers. One (4.76%) had suffered a pneumothorax in the past. Six (28.57%) declared occasionally using a stress management technique (meditation, self-hypnosis, cardiac coherence, autonomous sensory meridian response). Seventeen were right-handed (81%), and the remainder left-handed. Average height *Mheight* = 178 ± 9.41 meters, and weight *Mweight* = 71.1 ± 13 kilos. Table 1 reports full sociodemographic characteristics.

Table 1

Socio-demographic characteristics of participants

Measurements	Data*
N	21
Mage	22 ± 6.3
Mheight	178 ± 9.41
Mweight	71.1 ± 13
Gender (women/men)	33.33%/66.66%
Contraception	28.57%
Smokers	14.28%
Clinical medical history (i.e., pneumothorax)	4.76%
Stress management technics	28.57%

*Mean and standard deviation are reported when necessary. Other figures show the ratio of the number of subjects.

2.3. Data collection

2.3.1. Subjective measurements

Sociodemography. A 18-item sociodemographic questionnaire was developed to collect general information on the participant's family situation, medical history, current health status, hobbies, and familiarity with extreme environments.

Health. The General Health Questionnaire (GHQ) assesses the overall health status of subjects (12 items) (Shevlin & Adamson, 2005). The GHQ-12 was applied using a 4-point scale, and the timeframe of « in the last week ». The Leeds Sleep Evaluation questionnaire (LEEDS) evaluates perceived sleep changes, as a function of four sub-factors: sleep onset, sleep quality, sleep arousal, and performance (10 items) (Parrott & Hindmarch, 1980). Four additional items were added from the Buguet sleep questionnaire to evaluate the individual's overall status after sleep: desire to work, physical shape; morale; and mood (Buguet et al., 1981).

Psychology. The Multidimensional Assessment of Interoceptive Awareness evaluates interoceptive awareness (32 items) (Mehling et al., 2012). The scale is divided into eight sub-factors that measure awareness of uncomfortable, comfortable, and neutral body sensations, the response to sensations of pain and discomfort, the ability to regulate attention to body sensations, and awareness of mind-body integration (i.e., noticing, not distracting, not worrying, attention regulation, emotional awareness, self-regulation, body listening, trusting). The Scale of Positive and Negative Experience assesses subjective feelings of positive and negative affect, based on how frequently they were felt over the previous four weeks (12 items) (Martin-Krumm et al., 2018). The scale is divided into two sub-factors: positive and negative affect. The Activation-Deactivation Adjective Checklist evaluates the level of awareness and emotional disposition (28 items). The scale is divided into two sub-factors: Energetic Arousal (EA, from energy to tiredness) and Tense Arousal (TA, from tension to calmness). EA is further divided into two subscales: general activation and deactivation; and TA is subdivided into general tenseness and calmness (Thayer, 1967). The Perceived Stress Scale assesses the subjective stress level (14 items) (Cohen et al., 1983).

Extrasensors. The Sensory Gating Inventory evaluates abnormal perceptual salience with respect to four sub-factors: perceptual modulation, over-inclusion, distractibility, and sensory fatigue (36 items) (Micoulaud-Franchi et al., 2014). The Homemade Sensory Questionnaire measures subjective exteroceptive acuity for each of the exterosensors: vision, sound, touch, olfaction, taste, and equilibrium (6 items). The Personal Evaluation of Six Senses questionnaire assesses subjective perceptions of vision, sound, touch, olfaction, taste, and equilibrium (1 item). The Scale of Body Connection assesses mind-body awareness, divided into two sub-factors: body awareness and body dissociation (20 items) (Price & Thompson, 2007).

2.3.2. Cognition measurements

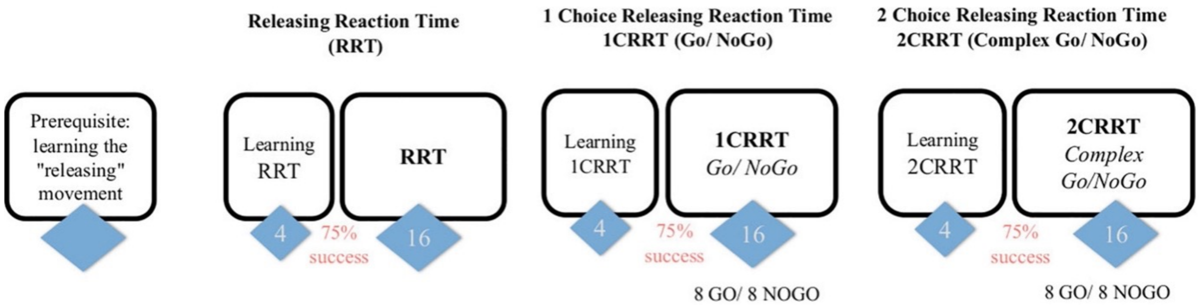
Cognitive performance was evaluated using the MindPulse test, developed by Suarez et al. (2021), which assesses decision-making. Subjects are seated in front of a computer screen that shows images requiring a response (instructions are displayed on the screen). The test battery consists of three tests of increasing complexity. Each test begins with a learning phase consisting of four trials, followed by a test phase. Different image packages are used for learning and test phases. Each image is presented only once to avoid any learning effect.

The first test consists of a *Releasing Reaction Time Task* (RRT). The participant is prompted to click down on a mouse button and must maintain the pressure until a stimulus (an image is presented in the center of the screen on a white background) appears. At this point, the button is released. Then the screen remains blank for between 2 and 7 seconds before another prompt appears to press down on the mouse button. When a new image is shown on the screen, the mouse must be released as fast as possible. The participant may practice as many times as necessary.

The second *1 Choice Releasing Reaction Time* (1CRRT) test consists of a Go/No-Go task. Here, the participant is instructed to only respond immediately (release the mouse button) to images of a certain color (white or gray, chosen randomly at the beginning of the test). If the image does not satisfy the color criteria, the subject maintains the pressure until prompted to release the button (after 3 seconds). The third, *2 Choice Releasing Reaction Time* (2CRRT) test also consists of a Go/No-Go task. In this case, the participant must only respond to an image that meets two criteria (the other color from the 1-choice task, and an animate or inanimate object, chosen randomly).

The computer records Reaction Time (RT) and response quality (the number and type of errors) for each trial. RT is divided into three main components: Simple Reaction Time (SRT), Executive Speed (ES), and Reaction to Difficulty (RD). Figure 1 presents an overview of the MindPulse battery of tests.

Figure 1
Overview of the MindPulse test battery. Figure reproduces from Suarez et al. (2021).



The test begins with training trials to learn the releasing movement. This step is followed by three tests of increasing complexity. The first Releasing Reaction Task (RRT) consists of 16 trials. The second, 1 Choice Releasing Reaction Task (1CRRT), and the third 2 Choice Releasing Reaction Task (2CRRT) tests each consist of eight Go and eight NoGo trials.

2.3.3. Exteroceptive measurements

Vision. The Parinaud scale (the French equivalent to the Jaeger chart) was used to measure the individual's natural accommodation (from the tip of the nose to the reading surface, measured with a tape measure), and shortest and longest possible accommodation when reading paragraphs of text in decreasing font size. The recommended reading distance to test visual acuity is 33 cm, with tolerance ranging from 30–35cm. Luminance was controlled with a luxmeter to ensure that the lighting environment was the same for all subjects.

Audition. The Loudness Discomfort Level (LDL) is commonly used to test hearing in patients who may be intolerant to sound. In subjects with normal hearing, it is evaluated using pulsed, ascending tones at frequencies of 500 Hz, 1000 Hz, 2000 Hz, 4000 Hz and 8000 Hz, until the individual reports a feeling of discomfort. In our study, volunteers were placed in a quiet room and told: « You will hear sounds that will become louder.

Raise your hand when the sound becomes unbearable, and it will stop immediately. The aim of the test is to identify when the sound's intensity leads to discomfort, and not to distinguish if it is loud or quiet. For example, the sound might be loud, but not uncomfortable ». About 90% of subjects reported discomfort at intensities ranging from 90–105 db. Stimuli were recorded and presented using the Electonica 600M system. Each stimulus was presented for approximately two seconds, with an interval of approximately one second between each presentation, until the subject reported discomfort.

Olfaction. The European Test of Olfactory Capabilities assesses olfactory sensitivity. Individuals are asked to select a bottle (there are 16 sets of four bottles) that contains a specific odor (a discrimination task) and state the nature of this odor (an identification task). In our experiment, participants were also asked to evaluate the hedonic value of the detected odor.

Gustation. Burghart taste strips measure acuity for four of the five basic tastes: bitter, sour, sweet and salty. For cultural reasons, umami, which is the fifth basic taste, was not investigated in this study. The test measures both the taste detection threshold, and the identification of flavors.

Proprioception. Posturography was assessed using a stabilometric static platform (Stabilotest). Subjects were asked to stand for one minute with their eyes open, and for one minute with their eyes closed. Among the numerous metrics used to characterize postural stability reported in the literature (Takagi et al., 1985; Winter et al., 1990), we assessed the most frequent measures: weight distribution between left and right feet; sway length; standard deviation along sagittal (antero-posterior) and frontal (medio-lateral) planes; elliptic surface; slope; and Center of Pressure (CoP) mean velocity and its variance.

2.3.4. HRV

Heartbeat interval data (RR) were recorded for a ten-minute period to extract heartbeat interval data (RR), with subjects in a sitting position, using a Polar H10 pectoral chest belt (Polar, Finland), at a sampling frequency of 180 Hz. The literature confirms the reliability of the Polar H10 belt to measure HRV (Georgiou et al., 2018; Järvelin-Pasanen et al., 2018; Speer et al., 2020; Umair et al., 2020; Zachariah & Joseph, 2019), and its use has been validated in a military population (Hinde et al., 2021). Furthermore, it has been shown to be as accurate as a reference ECG at rest, and during exercise (Gilden-Ammann et al., 2019). This device's low artifact rate makes it the best-available portable tool for recording cardiac activity, especially in studies in ecological environments. Three sensors pick up electrical signals from the heartbeat, which are sent in real time, via Bluetooth, to a software application (Manonen, 2019).

The HRV analysis followed guidelines reported in (Laborde et al., 2017; Task Force, 1996), which take into account potential circadian variation, and used the *PyHRV* python library (Gomes et al., 2019). The following data were recorded: weight; height; waist-to-hip ratio; smoking habits; most recent alcohol intake (>24h); most recent caffeinated (coffee/ tea) intake (>1h); most recent meal (>2h); most recent physical activity (>12h); and quality of sleep on the day of the experiment and the preceding day.

Raw ECG data were filtered between 3 and 45 Hz using a finite impulse response band-pass filter. The order of the filter was set at 54 (0.3 times the sampling frequency). R peaks were automatically detected using the *BioSPPy* python library (Carreiras et al., 2015). A Hamilton segmentation was performed on the filtered signal, followed by R-peak correction with tolerance set to 0.05. R-waves were manually examined to ensure correct detection. If an ECG sequence was overly noisy when visualizing the superposition of all QRS complex, the time interval was manually removed to improve data quality. RR intervals were automatically detected with the *hrvanalysis* module using linear interpolation, and manually corrected for artifacts and ectopic beats.

Time domain analysis. Time domain HRV metrics included mean RR (the mean interbeat interval), SDNN (Standard Deviation of the Normal-to-Normal RR interval), RMSSD (Root Mean Square of Successive Differences between adjacent RR intervals), and pNN50 (percentage of adjacent NN intervals that differ from each other by more than 50 ms).

Frequency domain analysis. Frequency domain HRV metrics complemented time domain metrics and included oscillatory components of heart rate dynamics. Spectral density was estimated using Welch's method: low frequencies (sympathetic and parasympathetic activity) in the range 0.04–0.15 Hz, and high frequencies (parasympathetic activity) in the range 0.15–0.4 Hz.

Nonlinear analysis. Nonlinear HRV metrics reflect dynamic and chaotic internal states that other metrics cannot reflect. The most representative metrics were used: the poincaré plot (i.e., graphical representation of the correlation between successive interbeat intervals), SD1 (i.e., standard deviation of instantaneous interbeat interval variability), SD2 (i.e., standard deviation of continuous, long-term RR variability), α1 (i.e., detrended fluctuation analysis self-similarity parameter that represented short-term fluctuations), α2 (i.e., detrended fluctuation analysis self-similarity parameter that represented long-term fluctuations), sample entropy (i.e., regularity and complexity of time series).

2.4. Experimental design

The survival experiment was run during the first week of May 2022, at the Marseille Naval Fire Battalion (France). On the first day, participants were transported to the Frioul archipelago (Marseille, France) and boarded a lifeboat canoe (n = 10), or an inflatable raft (n = 11). The craft were anchored behind the offshore islands in order to isolate them from boats entering the port of Marseille, and to cut off any view of the mainland (43°16.29'N 005°17.29'E). They remained on the craft for five days, with only a VHF radio to communicate with the base station in case of emergency. They were provided with a daily ration of food (a survival ration cube). Water was filtered to ensure sufficient daily intake, without excessive sodium. Sea temperature oscillated between 16–17°C, with wave height ranging from 0.5–0.6m. Participants were randomly allocated to either the lifeboat canoe or the raft, except for two firemen allocated to each of the craft for security.

Baseline assessments were performed the day before the experiment (D−1). Post-survival assessments were conducted on day 5 (D+5). Recovery assessments took place during the following week (D+7 to D+10). Cognition, exteroception and HRV were assessed twice, at D−1 and D+5. All subjective measurements were recorded during all three sessions, except for GHQ, which was only recorded at baseline (D−1).

2.5. Statistical methods

Statistics were computed for all outcome measures. Data analyses were performed with JASP (Amsterdam, version 0.16.3), an open-source software package that is used for both classical and Bayesian analyses. Descriptive statistics were expressed as mean ±

SD. The Shapiro–Wilk test was used to determine whether data were normally distributed. When the analysis was significant, effect sizes were reported. Both *t*-tests and non-parametric Wilcoxon signed rank analyses were used to evaluate pre- and post-experiment differences in the cognitive performance of survivors, as a function of the data distribution. Psychological, physiological and sensory states were evaluated using ANOVA or non-parametric Kruskal-Wallis signed rank analyses.

Tukey *post hoc* analyses were performed when the *p*-value was significant. Bayesian analyses were performed, by applying equivalent analyses for *t*-test and ANOVA analyses. The Bayesian Factor was calculated if no significant effect was detected. A low value provides support for the null hypothesis, and a high value indicates evidence in favor of the alternative hypothesis (Supplementary Material). For all analyses, statistical significance was set at $p < .05$. A *p*-value between .05 and .07 was considered as evidence of a trend.

3. Results

Baseline measurements for all participants are presented in Tables 2–7 (Supplementary Material). No difference was found between the two groups, apart from proprioception, where a difference was found for right-left asymmetry in the distribution of body weight with eyes open and closed (Table 5).

Table 2

Baseline health measurements among lifeboat and life raft embarcations

	Lifeboat (N = 10)	Life raft (N = 11)	*p*-value*
GHQ			
Mental health	11.000 ± 3.887	10.182 ± 3.250	.606
Sleep			
Sleep onset	2.300 ± 4.001	.636 ± 4.411	.378
Quality of sleep	-.700 ± .2.751	-.182 ± 2.316	.645
Sleep arousal	.300 ± 3.592	-.182 ± 5.845	.825
Performance	2.800 ± 3.676	3.909 ± 3.936	.514
Buguet			
Desire to work	2.400 ± 1.647	2.273 ± 2.149	.881
Physical feeling	.900 ± .876	1.455 ± 1.440	.306
Moral feeling	4.600 ± 1.174	4.636 ± 1.286	.947
Mood	5.200 ± .789	4.909 ± .944	.455

*p-value used in the analysis of effects (independent t-test or Mann-Whitney test). Means and standard deviation are show for each variable. All variables were recorded before and after 5 days of survival at sea. Only significant interactions and trends were reported (p<.07).

Table 3

Baseline psychology measurements among lifeboat and life raft embarcations

	Lifeboat (N = 10)	Life raft (N = 11)	*p*-value*
GHQ			
Mental health	11.000 ± 3.887	10.182 ± 3.250	.606
Sleep			
Sleep onset	2.300 ± 4.001	.636 ± 4.411	.378
Quality of sleep	-.700 ± .2.751	-.182 ± 2.316	.645
Sleep arousal	.300 ± 3.592	-.182 ± 5.845	.825
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Buguet			
Desire to work	2.400 ± 1.647	2.273 ± 2.149	.881
Physical feeling	.900 ± .876	1.455 ± 1.440	.306
Moral feeling	4.600 ± 1.174	4.636 ± 1.286	.947
Mood	5.200 ± .789	4.909 ± .944	.455
FMI			
Presence	17.700 ± 2.111	17.364 ± 3.613	.800
Acceptation	22.123 ± 3.151	19.809 ± 2.885	.870
MAIA			
Noticing	14.667 ± 2.646	14.200 ± 2.150	.677
Not distracting	7.667 ± 1.225	7.500 ± 1.716	.812
Not worrying	11.111 ± 1.764	10.200 ± 2.150	.330
Attention regulation	23.000 ± 2.449	13.100 ± 2.885	.936
Emotional awareness	17.222 ± 3.232	17.900 ± 3.814	.683
Self-regulation	12.222 ± 2.991	12.500 ± 2.273	.821
Body listening	7.889 ± 2.369	7.800 ± 2.394	.936
Trusting	12.111 ± 2.619	12.900 ± 1.969	.465
AD-ACL			
General activation	9.000 ± 2.357	10.364 ± 3.880	.349
Deactivation	3.200 ± 1.989	5.636 ± 3.641	.154
General tenseness	4.600 ± 3.026	2.545 ± 2.252	.092
Calmenss	8.700 ± 2.359	8.455 ± 3.142	.843
Arousal level	4.427 ± 4.211	3.385 ± 3.573	.547
Emotion			
Positive affects	2.950 ± .416	2.985 ± .444	.855
Negative affects	1.783 ± .741	1.561 ± .382	.391

PSS			
Subjective stress	22.450 ± 7.596	24.636 ± 10.298	.590

*p-value used in the analysis of effects (independent t-test or Mann-Whitney test). Means and standard deviation are show for each variable. All variables were recorded before and after 5 days of survival at sea. Only significant interactions and trends were reported (p<.07).

Table 4

Baseline perceptive sensory measurements among lifeboat and life raft embarcations

	Lifeboat (N = 10)	Life raft (N = 11)	*p*-value*
SGI			
Perceptual modulation	15.900 ± 7.325	20.455 ± 9.832	.247
Over inclusion	13.000 ± 3.127	11.455 ± 4.677	.390
Distractibility	13.900 ± 3.725	16.909 ± 5.890	.183
Fatigue stress modulation	8.300 ± 2.003	9.091 ± 3.618	.549
hOq			
Vision	2.200 ± 1.814	1.364 ± .809	.233
Hearing	2.500 ± 1.509	2.727 ± 1.489	.732
Olfaction	4.400 ± 1.430	3.727 ± 1.348	.281
Taste	5.100 ± 1.197	4.182 ± 1.537	.146
Touch	3.000 ± 1.155	3.909 ± 1.446	.130
Equilibrium	3.700 ± 1.947	4.545 ± 1.440	.269
PESS			
Vision	7.700 ± 1.059	7.273 ± 1.954	.547
Hearing	8.200 ± 2.044	7.909 ± 1.044	.443
Olfaction	7.100 ± 1.792	6.364 ± 2.248	.420
Taste	7.500 ± 1.269	6.909 ± 2.212	.468
Touch	8.200 ± 1.619	6.909 ± 1.640	.086
Equilibrium	7.600 ± 2.413	7.273 ± 1.489	.710
SBC			
Body awareness	2.399 ± .448	2.235 ± .473	.426
Body dissociation	1.426 ± 1.058	1.114 ± .501	.391

*p-value used in the analysis of effects (independent t-test or Mann-Whitney test). Means and standard deviation are show for each variable. All variables were recorded before and after 5 days of survival at sea. Only significant interactions and trends were reported (p<.07).

Table 5

Baseline exteroceptive measurements among lifeboat and life raft embarcations

	Lifeboat (N = 10)	Life raft (N = 11)	*p*-value*
Parinaud			
Minimum	34.000 ± 7.427	36.136 ± 7.349	.516
Maximum	14.250 ± 3.918	13.409 ± 5.064	.678
Accommodation	91.300 ± 27.268	74.591 ± 19.239	.118
Hearing			
500 Hz (right ear)	91.500 ± 6.258	93.636 ± 2.335	.723
1000 Hz (right ear)	91.500 ± 2.415	92.273 ± 4.671	.645
2000 Hz (right ear)	91.000 ± 7.379	93.636 ± 6.742	.403
4000 Hz (right ear)	89.000 ± 3.162	90.000 ± .000	**< .05**
8000 Hz (left ear)	87.000 ± 4.830	88.182 ± 4.045	.549
500 Hz (left ear)	94.000 ± 2.108	94.091 ± 2.023	.921
1000 Hz (left ear)	90.500 ± 5.986	91.818 ± 2.523	.511
2000 Hz (left ear)	88.000 ± 7.888	90.909 ± 5.394	.332
4000 Hz (left ear)	87.000 ± 6.749	89.091 ± 3.015	.363
8000 Hz (left ear)	87.000 ± 6.749	87.273 ± 4.671	.915
ETOC			
Detection	15.800 ± .422	16.000 ± .000	**< .05**
Identification	12.800 ± 2.860	13.636 ± 2.860	.721
Hedonic value	63.635 ± 8.210	62.886 ± 8.754	.842
Taste strip			
Taste	17.100 ± .994	17.273 ± .786	.662
Proprioception			
Weight distribution on the left foot in open eyes condition (%)	47.100 ± 4.303	50.618 ± 2.989	**.041**
Weight distribution at front left foot in open eyes condition (%)	22.840 ± 4.453	30.018 ± 5.427	**.004**
Weight distribution at rear left foot in open eyes condition (%)	24.280 ± 4.521	20.609 ± 5.603	.117
Weight distribution on the right foot in open eyes condition (%)	52.900 ± 4.303	49.382 ± 2.989	**.041**
Weight distribution at front right foot in open eyes condition (%)	24.800 ± 4.047	28.864 ± 5.013	**.057**
Weight distribution at rear right foot in open eyes condition (%)	28.120 ± 5.600	20.527 ± 4.890	**.004**
IVV in open eyes condition	-.114 ± .283	-.119 ± .145	.960
Slope in open eyes condition	.822 ± 4.013	-.026 ± 2.888	.582

Average CoP left to right in open eyes condition (mm) in open eyes condition	5.671 ± 9.386	-.983 ± 9.287	.119
Average CoP front to rear in open eyes condition (mm) in open eyes condition	23.733 ± 8.928	45.419 ± 16.460	**.001**
Ellipse surface in open eyes condition (mm)	122.211 ± 80.012	199.501 ± 163.717	.193
Logarithm in open eyes condition (mm)	461.095 ± 154.535	433.704 ± 109.107	.642
Logarithm left to right in open eyes condition (mm)	230.999 ± 96.410	213.246 ± 62.348	.619
Logarithm front to rear in open eyes condition (mm)	349.884 ± 112.015	331.360 ± 82.252	.669
AN02 left to right in open eyes condition	23.488 ± 16.477	8.546 ± 6.782	**.012**
AN02 front to rear in open eyes condition	9.662 ± 6.898	10.186 ± 10.323	.894
Average speed in open eyes condition (mm/s)	9.012 ± 3.020	8.475 ± 2.132	.641
Average speed variation in open eyes condition (mm/s)	471.569 ± 1350.440	285.885 ± 784.563	.701
LFS in open eyes condition	1.042 ± .300	.922 ± .174	.269
VFY in open eyes condition	4.758 ± 19.482	-4.625 ± 17.689	.262
Standard deviation left to right in open eyes condition	2.056 ± .973	2.902 ± 1.270	.106
Standard deviation front to rear in open eyes condition	4.281 ± 1.310	4.685 ± 2.156	.614
Weight distribution on the left foot in closed eyes condition (%)	42.443 ± 15.301	52.136 ± 3.454	**.054**
Weight distribution at front left foot in closed eyes condition (%)	23.080 ± 4.671	29.836 ± 6.092	**.011**
Weight distribution at rear left foot in closed eyes condition (%)	23.610 ± 4.397	22.300 ± 5.015	.534
Weight distribution on the right foot in closed eyes condition (%)	53.320 ± 4.249	47.864 ± 3.454	**.004**
Weight distribution at front right foot in closed eyes condition (%)	24.910 ± 2.975	27.345 ± 3.382	.097
Weight distribution at rear right foot in closed eyes condition (%)	28.440 ± 5.107	20.527 ± 5.120	**.002**
IVV in closed eyes condition	-.089 ± .194	-.020 ± .215	.453
Slope in closed eyes condition	.781 ± 3.680	1.000 ± 3.402	.889
Average CoP left to right in closed eyes condition (mm) in open eyes condition	6.992 ± 10.811	-3.269 ± 6.189	**.014**
Average CoP front to rear in closed eyes condition (mm) in open eyes condition	18.856 ± 12.994	46.834 ± 20.124	**.001**
Ellipse surface in closed eyes condition (mm)	202.360 ± 130.600	198.636 ± 139.672	.950
Logarithm in closed eyes condition (mm)	637.700 ± 348.807	545.464 ± 152.182	1.000
Logarithm left to right in closed eyes condition (mm)	302.921 ± 196.775	257.328 ± 90.376	.918
Logarithm front to rear in closed eyes condition (mm)	496.537 ± 252.437	426.275 ± 123.858	.421
AN02 left to right in closed eyes condition	35.018 ± 66.047	19.867 ± 17.073	.471
AN02 front to rear in closed eyes condition	12.917 ± 10.530	14.246 ± 9.009	.759
Average speed in closed eyes condition (mm/s)	12.462 ± 6.814	10.659 ± 2.975	1.000

Average speed variation in closed eyes condition (mm/s)	108.715 ± 113.235	217.386 ± 456.583	.474
LFS in closed eyes condition	1.323 ± .627	1.158 ± .232	.860
VFY in closed eyes condition	2.297 ± 5.688	-5.321 ± 7.189	**.015**
Standard deviation left to right in closed eyes condition	2.867 ± .997	2.845 ± .992	.961
Standard deviation front to rear in closed eyes condition	5.199 ± 1.682	4.655 ± 1.971	.507

*p-value used in the analysis of effects (independent t-test or Mann-Whitney test). Means and standard deviation are show for each variable. All variables were recorded before and after 5 days of survival at sea. Only significant interactions and trends were reported (p<.07).

Table 6

Baseline physiology measurements among lifeboat and life raft embarcations

	Lifeboat (N = 10)	Life raft (N = 11)	p-value*
HRV			
RR intervals	738.411 ± 87.455	798.562 ± 72.605	.101
SDNN	66.414 ± 15.550	80.226 ± 22.511	.122
RMSSD	64.341 ± 8.865	70.659 ± 8.696	.116
pNN50	45.854 ± 7.358	48.754 ± 4.913	.297
LF	.076 ± .027	.075 ± .024	.914
HF	.241 ± .059	.249 ± .060	.739
LF/HF ratio	1.397 ± .976	1.630 ± .651	.524
SD1	45.496 ± 6.268	49.963 ± 6.149	.116
SD2	81.591 ± 23.020	101.355 ± 32.599	.129
SD ratio	1.790 ± .435	2.002 ± .435	.278
α1	.904 ± .172	1.016 ± .130	.105
α2	.803 ± .122	.791 ± .165	.850
Sample entropy	2.017 ± .166	1.893 ± .149	.087

*p-value used in the analysis of effects (independent t-test or Mann-Whitney test). Means and standard deviation are show for each variable. All variables were recorded before and after 5 days of survival at sea. Only significant interactions and trends were reported (p<.07).

Table 7

Baseline cognitive measurements among lifeboat and life raft embarcations

	Lifeboat (N = 10)	Life raft (N = 11)	*p*-value*
Cognition	-	-	-
SRT	372.438 ± 47.620	357.483 ± 64.965	.672
ES	247.396 ± 68.656	245.066 ± 69.913	.955
Overall precision	3.400 ± 1.817	2.857 ± 1.773	.616
RD	.106 ± .112	-.031 ± .199	.197
Errors of ommission precision	.000 ± .000	.000 ± .000	**< .05**
Abbreviated answers accuracy	1.400 ± 1.342	.286 ± .488	.146
SRT dispersion	73.380 ± 41.191	42.983 ± 24.363	.138
Accuracy of choice errors	2.200 ± 1.483	2.000 ± 1.633	.833
RT dispersion with categorization	158.314 ± 42.770	126.274 ± 69.939	.387
Total errors accuracy	3.400 ± 1.817	2.857 ± 1.773	.616
Dual speed categorization	840.284 ± 123.819	780.303 ± 251.272	.636
Errors related to the introduction of a second choice	.000 ± .000	.429 ± .787	**< .05**
Go/noGo speed	596.956 ± 109.586	603.353 ± 101.100	.919
Inhibition errors	1.000 ± 1.225	.286 ± .488	.187
Anticipation errors	1.200 ± 1.643	.857 ± .900	.650

**p*-value used in the analysis of effects (independent t-test or Mann-Whitney test). Means and standard deviation are show for each variable. All variables were recorded before and after 5 days of survival at sea. Only significant interactions and trends were reported ($p<.07$).

3.1. Health and psychological state

Sleep quality. There were significant effects of time on difficulty in falling asleep [$F(2,54) = 11.319$, $p < .001$, $\eta^2 = .295$], length of time to fall asleep [$F(2,54) = 5.694$, $p = .006$, $\eta^2 = .174$], difficulty in waking up [$F(2,54) = 15.481$, $p < .001$, $\eta^2 = .364$], time to wake up [$F(2,54) = 17.549$, $p < .001$, $\eta^2 = .394$], balance/coordination on waking [$F(2,54) = 12.306$, $p < .001$, $\eta^2 = .131$], time to get up [$F(2,54) = 7.084$, $p = .002$, $\eta^2 = .208$], and sleep time [$F(2,54) = 4.604$, $p = .014$, $\eta^2 = .146$]. *Post hoc* analyses revealed that participants found it more difficult to fall asleep ($p <.001$), slept for less time ($p = .009$), woke up more easily ($p = .007$) and more quickly ($p < .001$), had poorer balance and coordination ($p = .081$), fell asleep earlier ($p = .001$) and got up earlier ($p = .010$) at the end of the experiment compared to before.

Thymia. There were significant effects of time on general activation [F(2,54) = 9.436, $p < .001$, $\eta^2 = .259$], deactivation [F(2,54) = 10.810, $p < .001$, $\eta^2 = .286$], and arousal [F(2,54) = 10.010, $p < .001$, $w^2 = .240$]. *Post hoc* analyses showed that the level of general activity was lower (p <.001), deactivation was higher (p < .001), and arousal was lower (p < .001) at the end of the experiment compared to before.

Perceptions of energy. There were significant effects of time on desire to work [F(2,54) = 3.085, $p < .001$, $\eta^2 = .103$] and physical feeling [F(2,54) = 20.257, $p < .001$, $\eta^2 = .429$]. *Post hoc* analyses found that participants had more desire to work (p < .001) and felt better physically (p < .001) at the end of the experiment.

Subjective stress. There was a significant effect of time on stress [F(2,54) = 3.716, $p = .031$, $\eta^2 = .121$]. *Post hoc* analyses revealed that participants tend to perceive less stress at the end of the experiment (p = .063).

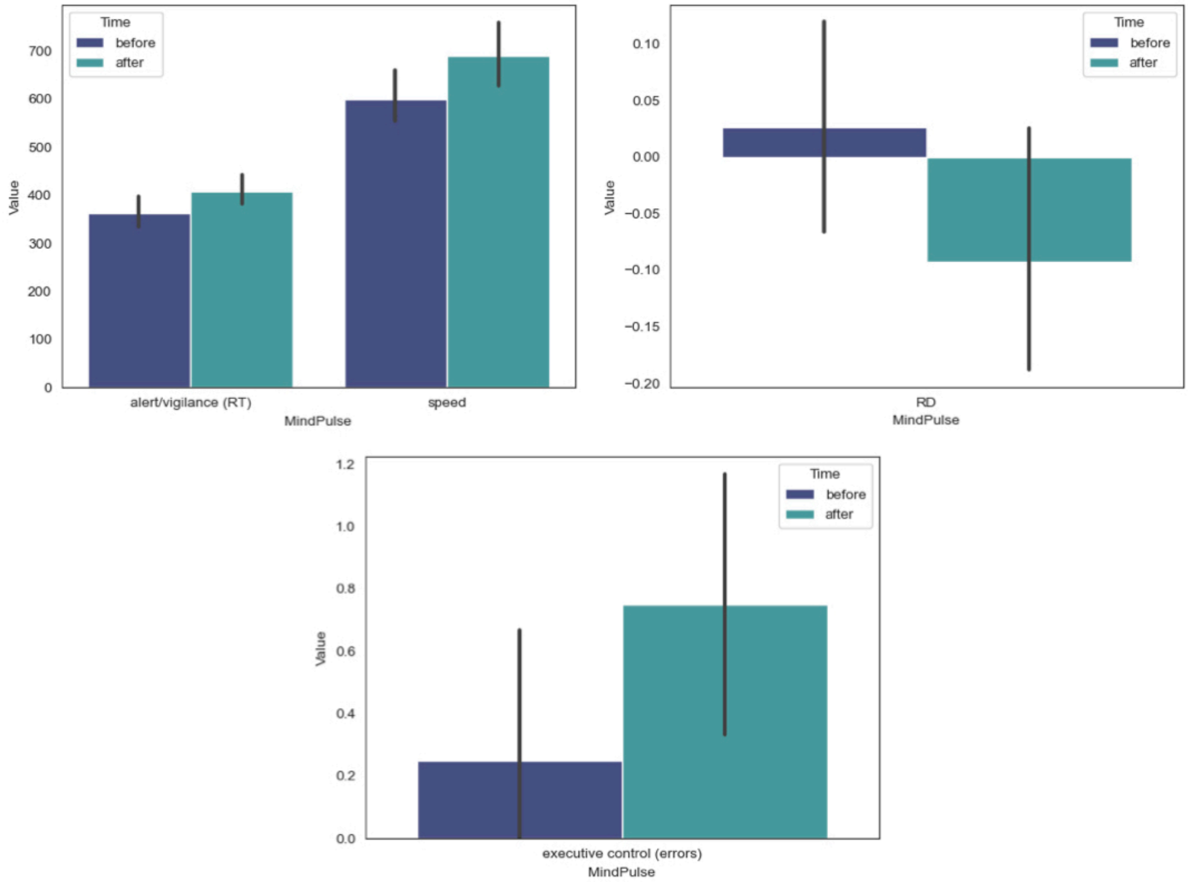
Subjective exteroceptive acuity. There were significant effects of time on posture [F(2,54) = 6.236, $p = .013$, $w^2 = .155$] and a trend was identified for touch [F(2,54) = 2.841, $p = .067$, $\eta^2 = .095$]. *Post hoc* analyses showed that participants had reduced ability to feel changes in their body (p = .002) and tended to have a poorer grasp of their tactile environment (p = .056) at the end of the experiment compared to before.

3.2. Cognitive performance and physiological/sensory functioning

Cognition. Overall, RD tended to be lower (t = 1.949, df = 11, p = .077, d = .563) post-experiment. For the alert/vigilance function, RT was higher (t = −4.192, df = 11, p = .002, d = −1.210). For the executive control function, the number of errors related to the 2CRRT (W = 0.000, p = .048, r = −1.000), and speed in Go/noGo tasks (t = −3.985, df = 11, p = .002, d = −1.150) were higher post-experiment (Figure 2).

Figure 2

Cognitive performance throughout 5-days survival



Hearing. Significant differences were found for both ears. Two analyses were carried out. The first examined the results of the hearing discomfort threshold test, including the maximum value at which no discomfort was detected. For the right ear, the LDL was lower at 1000 Hz (W = 42, *p* = .021, r = .867), 2000 Hz (W = 15, *p* = .037, r = 1.000), and 4000 Hz (W = 21, *p* = .020, r = 1.000), and a trend was identified at 8000 Hz (W = 24, *p* = .073, r = .714). For the left ear, LDL was lower at 500 Hz (W = 56, *p* = .033, r = .697) and 8000 Hz (W = 21, *p* = .026, r = 1.000). The second analysis consisted of assigning the number 0 or 1 when hearing discomfort was detected below the maximum threshold. At 4000 Hz, the LDL was higher post-experiment for the right ear (W = .00, *p* = .020, r = −1.000). The LDL was higher both at 500 Hz (W = 21, *p* = .057, r = −.538), and 1000 Hz (W = 6.00, *p* = .008, r = −.818) for the left ear.

Olfaction. A significant difference was found for hedonic value (t = −2.102, df = 20, *p* = .048, d = −.459), which was higher post-experiment.

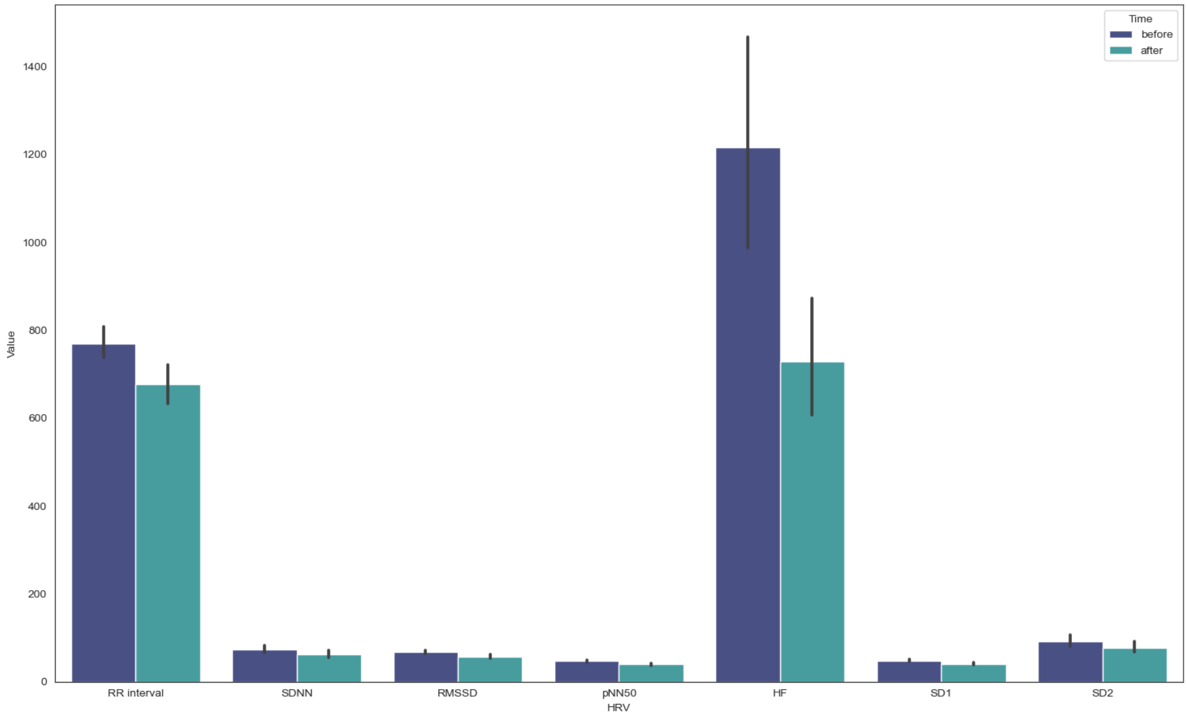
Proprioception. Significant differences were found in both open and closed eyes conditions. Specifically, the rear weight distribution for the left foot (W = 59, p = .050, r = −.489), and the right foot (W = 59, p = .050, r = −.489), ellipse surface (W = 17, p < .001, r = −.853), logarithm (W = 33, p = .003, r = −.714), logarithm left to right (W = 2, p < .001, r = −.983), logarithm front to rear (W = 23, p < .001, r = −.801), average speed (W = 33, p = .003, r = −.714), VFY (i.e., relationship between the displacement speed of the center of gravity and the average shift in Y) (W = 54, p = .032, r = −.532), and standard deviation front to rear (t = −3.493, df = 20, p = .002, d = −.762) were higher post-experiment in the open eyes condition, compared to the closed eyes condition. Front weight distribution tended to be higher for the right foot (W = 167, p = .076, r = .446) in the open eyes condition compared to the closed eyes one.

In the open eyes condition, average front to rear Centre of Pressure (CoP) was lower (t = 3.529, df = 20, p = .002, d = .770); and average speed variation tended to be lower (W = 64, p = .076, r = −.446). Left to right standard deviation (p = .288, BF_{10} = 18.064) was strongly associated with the slope in degrees (p = .168, BF_{10} = 1.705), which supported the alternative hypothesis in the open eyes condition. Thus, participants who increased their standard deviation left to right tended to decrease the slope in degrees after the survival experience.

In the closed eyes condition, average front to rear CoP (W = 0, p < .001, r = −1.000), ellipse surface (W = 3, p < .001, r = −.974), logarithm (W = 14, p < .001, r = −.879), logarithm left to right (W = 15, p < .001, r = −.870), logarithm front to rear (W = 13, p < .001, r = −.887), AN02 front to rear (W = 54, p = .032, r = −.532), average speed (W = 14, p < .001, r = −.879), average speed variation (W = 7, p < .001, r = −.939), VFY (W = 11, p < .001, r = −.905), standard deviation left to right (W = 16, p < .001, r = −.861), and standard deviation front to rear (t = −5.337, df = 20, p < .012, d = −1.165) were higher post-experiment.

HRV. The following significant differences were found: RR interval (t = 3.995, df = 20, p < .001, d = .872), SDNN (t = 2.152, df = 20, p = .044, d = .470), RMSSD (t = 4.802, df = 20, p < .001, d = 1.048), pNN50 (t = 4.975, df = 20, p < .001, d = 1.086), HF (t = 3.813, df = 20, p < .001, d = .832), SD1 (t = 4.802, df = 20, p < .001, d = 1.048) were lower post-experiment. A trend was identified for SD2 (t = 1.861, df = 20, p = .078, d = .406) (Figure 3).

Figure 3
Cardiac biosignal throughout 5-days survival



Tables 8 and 9 present a summary of these physiological and sensory differences, and cognitive performance following the experiment.

Table 8

Summary of the cognitive and physiosensory impact of 5 days survival at sea on participants

	Before the survival	After the survival	*p*-value*
Cognition			
RT (all confounded measures)	.026 ± .177	-.092 ± .197	.077
RT (alert/vigilance function)	363.714 ± 56.444	408.137 ± 56.517	.002
Number of errors related to the introduction of a second choice (executive control)	.250 ± .622	.750 ± .754	.048
Go/noGo speed (executive control)	600.688 ± 99.765	690.743 ± 124.276	.002
ETOC			
Hedonic value	63.243 ± 8.295	66.925 ± 8.971	.048
Hearing			
1000 Hz (right ear)	91.905 ± 3.700	89.048 ± 5.617	.021
2000 Hz (right ear)	92.381 ± 7.003	90.000 ± 7.071	.037
4000 Hz (right ear)	89.524 ± 2.182	86.667 ± 4.830	.020
8000 Hz (right ear)	87.619 ± 4.364	85.238 ± 6.016	.073
500 Hz (left ear)	94.048 ± 2.012	91.667 ± 4.564	.033
8000 Hz (left ear)	87.14 ± 5.60	83.80 ± 7.40	.026
LDL detection			
4000 Hz (right ear)	.42 ± .50	.71 ± .46	.020
500 Hz (left ear)	.23 ± .42	.57 ± .50	.057
1000 Hz (left ear)	.38 ± .49	.80 ± .40	.008
Proprioception			
Weight distribution at rear left foot in open eyes condition (%)	25.357 ± 5.331	25.157 ± 5.208	.050
Weight distribution at front right foot in open eyes condition (%)	26.929 ± 4.925	25.338 ± 6.624	.076
Weight distribution at rear right foot in open eyes condition (%)	24.143 ± 6.416	26.543 ± 7.925	.046
Average CoP front to rear in open eyes condition (mm)	35.092 ± 17.161	22.606 ± 14.858	.002
Ellipse surface in open eyes condition (mm)	162.696 ± 133.593	340.539 ± 361.517	< .001
Logarithm in open eyes condition (mm)	446.747 ± 129.981	594.877 ± 284.383	.003
Logarithm left to right in open eyes condition (mm)	221.700 ± 78.796	781.051 ± 836.987	< .001
Logarithm left to right in open eyes condition (mm)	340.181 ± 95.493	459.733 ± 194.009	< .001
Average speed in open eyes condition (mm/s)	8.731 ± 2.540	11.625 ± 5.556	.003
Average speed variation in open eyes condition (mm/s)	374.306 ± 1066.517	231.610 ± 594.935	.076
VFY in open eyes condition	18.717 ± 4.084	11.708 ± 2.555	.032
Standard deviation front to rear in open eyes condition	4.914 ± 1.815	6.170 ± 2.565	.002

Average CoP front to rear in closed eyes condition (mm)	33.511 ± 21.988	840.597 ± 449.791	< .001
Ellipse surface in closed eyes condition (mm)	200.410 ± 132.034	963.353 ± 1165.561	< .001
Logarithm in closed eyes condition (mm)	589.386 ± 261.835	1298.837 ± 996.597	< .001
Logarithm left to right in closed eyes condition (mm)	279.039 ± 148.501	781.051 ± 836.987	< .001
Logarithm front to rear in closed eyes condition (mm)	459.733 ± 194.009	840.597 ± 449.791	< .001
AN02 av/arr in closed eyes condition	13.613 ± 9.536	27.299 ± 27.001	.032
Average speed in closed eyes condition (mm/s)	11.518 ± 5.116	25.380 ± 19.474	< .001
Average speed variation in closed eyes condition (mm/s)	165.638 ± 336.299	651.609 ± 993.751	< .001
VFY in closed eyes condition	-1.693 ± 7.456	11.916 ± 15.179	< .001
Standard deviation left to right in closed eyes condition	2.856 ± .969	6.570 ± 5.481	< .001
Standard deviation front to rear in closed eyes condition	4.914 ± 1.815	8.401 ± 3.301	< .001
HRV			
RR intervals	769.918 ± 83.816	676.801 ± 108.200	< .001
SDNN	73.649 ± 20.301	62.494 ± 19.762	.044
RMSSD	67.650 ± 9.145	57.651 ± 8.902	< .001
pNN50	47.373 ± 6.216	39.660 ± 7.984	< .001
HF	1215.655 ± 562.640	728.183 ± 324.387	.001
SD1	47.836 ± 6.466	40.765 ± 6.294	< .001
SD2	91.943 ± 29.531	77.870 ± 28.480	.078

**p*-value used in the analysis of effects. Means and standard deviation are show for each variable. All variables were recorded before and after 5 days of survival at sea. Only significant interactions and trends were reported (p<.07).

Table 9

Summary of the psychological impact of extreme environment and recovery on participants

	Before the survival	After the survival	Recovery	*p*-value*
Interoception				
Attention regulation	23.053 ± 2.614	21.795 ± 3.689	20.158 ± 3.976	.044
Body listening	7.842 ± 2.316	8.895 ± 2.258	7.000 ± 2.867	.073
Thymia				
General activation	9.789 ± 3.392	5.250 ± 3.467	8.053 ± 2.857	< .001
Deactivation	4.263 ± 3.034	9.053 ± 3.674	7.474 ± 2.951	< .001
Arousal	4.097 ± 3.960	.789 ± .808	1.394 ± 1.152	< .001
Emotion				
Negative affect	1.640 ± .602	1.263 ± .554	1.228 ± .545	.053
Sleep quality				
Difficulty in falling asleep	-.053 ± 2.068	-2.947 ± 1.957	-.684 ± 1.887	< .001
Length of time to fall asleep	-.263 ± 1.661	-2.421 ± 2.610	-.474 ± 2.144	.006
Difficulty to wake up	.316 ± 1.945	2.421 ± 2.063	-1.263 ± 2.130	< .001
Length of wake up	-.526 ± 1.896	2.842 ± 2.035	-.947 ± 2.505	< .001
Awakening energy	.053 ± 2.223	-1.000 ± 2.160	-1.579 ± 1.502	.045
Fatigue	.816 ± 1.850	-.474 ± 2.170	-1.316 ± 1.701	.005
Balance/coordination on waking	3.158 ± 2.713	-.895 ± 3.365	-.632 ± 2.266	< .001
Time of getting up	.316 ± 2.083	-2.737 ± 2.725	-.947 ± 2.677	.002
Time of sleep	-.368 ± 2.033	-2.526 ± 2.547	-1.526 ± 1.954	.014
Perceptual energy				
Desire to work	2.211 ± 1.751	4.526 ± 1.837	2.305 ± 1.418	< .001
Physical feeling	1.105 ± 1.243	3.000 ± 1.374	3.789 ± 1.386	< .001
Subjective stress				
Stress	22.605 ± 8.792	17.353 ± 5.431	22.842 ± 6.397	.031
Sensory discrimination				
Perceptual modulation	19.211 ± 8.651	23.234 ± 8.615	28.053 ± 14.366	.051
Distractibility	15.105 ± 4.496	16.986 ± 4.949	21.632 ± 8.105	.009
Fatigue stress modulation	8.684 ± 2.907	9.579 ± 2.835	11.737 ± 4.629	.036
Subjective exteroceptive acuity				
Posture	7.684 ± 1.734	4.737 ± 3.212	6.263 ± 2.557	.013
Touch	7.632 ± 1.770	6.000 ± 2.728	7.000 ± 1.732	.067

**p*-value used in the analysis of effects. Means and standard deviation are show for each variable. All variables were recorded before and after 5 days of survival at sea. Only significant interactions and trends were reported ($p<.07$).

3.3. Measures at recovery (D+7 to D+10)

Interoception. There was a significant effect of time on attention regulation [$F(2,54) = 3.313$, $p = .044$, $\eta^2 = .109$] and a trend was identified for body listening [$F(2,54) = 2.749$, $p = .073$, $\eta^2 = .092$]. *Post hoc* analyses revealed that participants' attention to their body sensations fell ($p = .034$) and they tended to be less aware of their body sensations ($p = .059$) at recovery compared to D−1.

Thymia. There were significant effects of time on general activation [$F(2,54) = 9.436$, $p < .001$, $\eta^2 = .259$], deactivation [$F(2,54) = 10.810$, $p < .001$, $\eta^2 = .286$], and arousal [$F(2,54) = 10.010$, $p < .001$, $w^2 = .240$]. *Post hoc* analyses showed that participants had a lower level of general activity ($p = .027$), increased deactivation ($p = .010$), and lower arousal ($p < .001$) at recovery compared to D+5.

Emotion. There was a significant time effect on negative affect [$F(2,54) = 3.085$, $p = .053$, $\eta^2 = .103$]. *Post hoc* analyses found that participants tended to have less negative affect at recovery compared to D−1 ($p = .079$).

Sleep quality. There were significant effects of time on difficulty in falling asleep [$F(2,54) = 11.319$, $p < .001$, $\eta^2 = .295$], length of time to fall asleep [$F(2,54) = 5.694$, $p = .006$, $\eta^2 = .174$], difficulty in waking up [$F(2,54) = 15.481$, $p < .001$, $\eta^2 = .364$], time to wake up [$F(2,54) = 17.549$, $p < .001$, $\eta^2 = .394$], energy on wake [$F(2,54) = 3.287$, $p = .045$, $\eta^2 = .109$], fatigue [$F(2,54) = 5.959$, $p = .005$, $\eta^2 = .181$], balance/ coordination on waking [$F(2,54) = 12.306$, $p < .001$, $\eta^2 = .131$], time to get up [$F(2,54) = 7.084$, $p = .002$, $\eta^2 = .208$], and sleep time [$F(2,54) = 4.604$, $p = .014$, $\eta^2 = .146$]. *Post hoc* analyses revealed that participants felt that they were in worse physical shape ($p = .038$), woke up less easily ($p = .054$), felt more tired during the day ($p = .003$), and had poorer balance and coordination ($p = .001$) at recovery compared to D−1. However, they also had less difficulty falling asleep ($p = .002$), slept for longer ($p = .021$), woke up less easily ($p < .001$), and less quickly ($p < .001$), and tended to go to bed later ($p = .081$) at recovery compared to D+5.

Perception of energy. There were significant effects of time on desire to work [$F(2,54) = 3.085$, $p < .001$, $\eta^2 = .103$] and physical state [$F(2,54) = 20.257$, $p < .001$, $\eta^2 = .429$].

Post hoc analyses revealed les desire to work ($p < .001$) and feeling better physically ($p < .001$) at recovery compared to D+5.

Subjective stress. There was a significant effect of time on stress [F(2,54) = 3.716, $p = .031$, $\eta^2 = .121$]. *Post hoc* analyses showed that participants tended to perceive more stress at recovery compared to D+5 ($p = .050$).

Sensory discrimination. There were significant effects of time on perceptual modulation [F(2,54) = 3.143, $p = .051$, $\eta^2 = .104$], distractibility [F(2,54) = 5.827, $p = .009$, $w^2 = .145$], and fatigue stress modulation [F(2,54) = 3.702, $p = .036$, $w^2 = .087$]. *Post hoc* analyses revealed that participants were more sensitive to distraction ($p = .005$), had a greater ability to modulate and filter sensory stimuli ($p = .040$), and were more vulnerable to fatigue and stress ($p = .028$) at recovery compared to D−1. They were also more sensitive to distraction at recovery compared to D+5 ($p = .056$).

A summary of these psychological impacts and differences at recovery is presented in Table 9. Figures 4 to 6 reported the evolution of measures throughout survival.

Figure 4

Measures involving recovery throughout 5-days survival

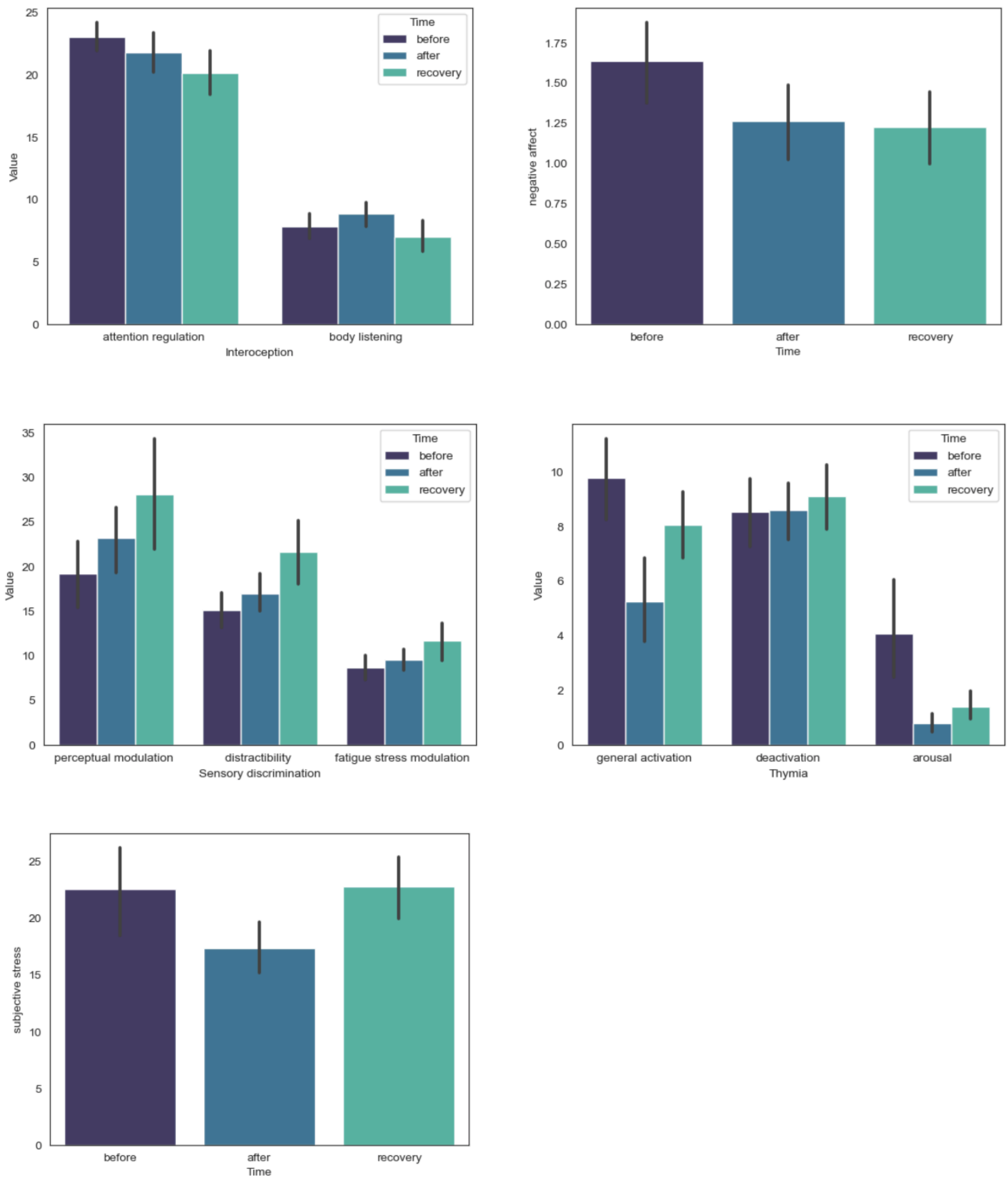


Figure 5
Sleep quality throughout 5-days survival

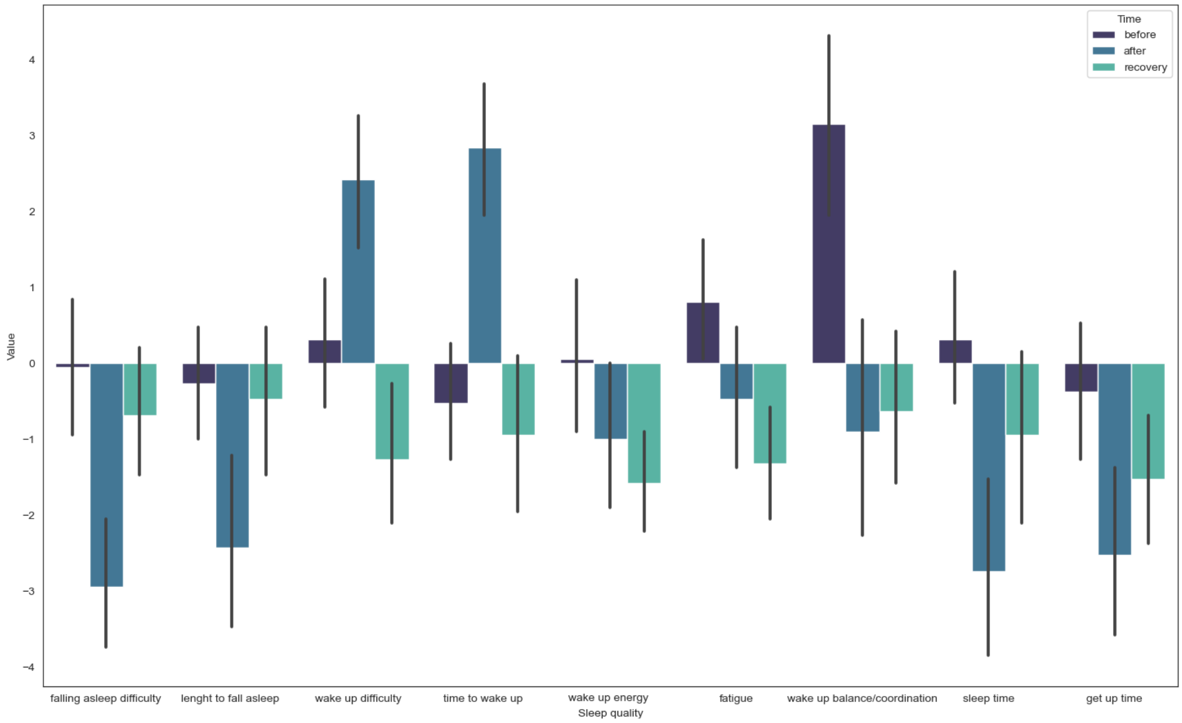
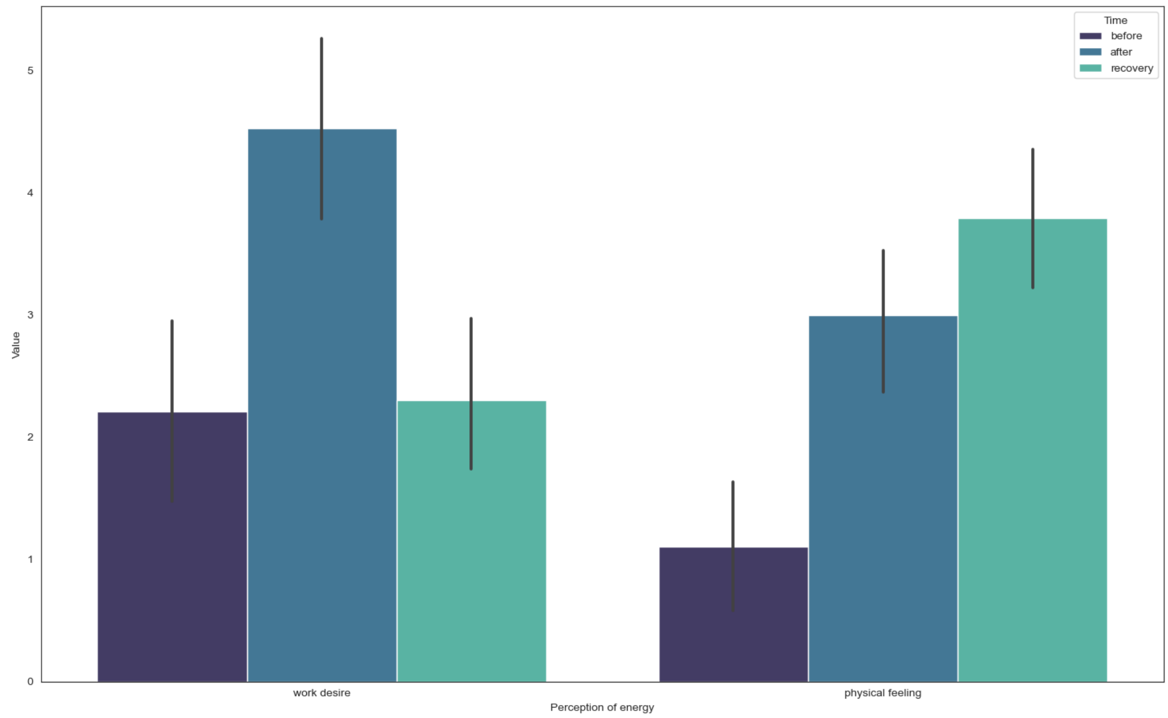


Figure 6
Perception of energy throughout 5-days survival



4. Discussion

Surviving for five days at sea is a challenging endeavor that is characterized by several aspects. Multiple stressors can potentially lead to a serious accident – or death – if not managed appropriately. DeHart (1985) highlighted that individuals must immediately accept the reality of the environment and react to their surroundings. While brain neuroplasticity enables the human body to efficiently adapt to changes in the environment in a few minutes, the quality of this adaptation in the longer term will differ depending on the resources and reserves that the individual is able to mobilize, as well as their physical and mental preparation. Overall, the health of our participants deteriorated during their five-day survival experience, and the deterioration persisted for several more days, for both those on the lifeboat and the life raft. Thus, this study highlights the enactive nature of human–environment interactions.

4.1. Are participants' responses adaptive?

Our study sheds light on several important findings. Psychological measures indicate that subjects feel better physically and perceive less stress at the end of the experiment. Several hypotheses may support this outcome—for example, they may have become disconnected from the stressors of their normal life. In another study, Plopa et al. (2020) showed that after six months at sea, some individuals reported increased anxiety, while others remained stable. Unless the reference frame is simply not the same as the real life, the results reflect another reality.

In our experiment, participants' sleep rhythm seems to shift. They fall asleep earlier, wake up more easily and more quickly, and get up earlier. These results may reflect a state of hypervigilance. On the other hand, we found evidence of sleep disturbance. They sleep for less time and have difficulties falling asleep. The literature reports that fatigue is dangerous and may degrade cognitive performance (Bardwell et al., 2005; Van Dongen et al., 2004).

They also have poorer balance and coordination. During their time at sea, they had no choice but to follow the roll of the waves, and their frame of reference changed to this new off-land environment. General activity was also reduced, and this was associated with a lower level of wakefulness and a greater tendency to sleep when back on land. On the other hand, participants have a greater desire to work after the experiment. This result highlights the lack of activity onboard; boredom was their companion.

The analysis of the cardiac bio-signal reveals a decrease in ANS activity (the RR interval, SDNN, RMSSD, pNN50, and HF fell) with lower flexibility indices in the short and long term, indicated by a fall in SD1 and SD2. However, neither parasympathetic nor sympathetic activity increases. The lack of an increase in sympathetic activity, in particular, is surprising. These results highlight weaker adaptive capacities with respect to non-linear cardiac flexibility indices. All HRV components were affected by the survival experience. They were associated with a decrease in body listening and increases in general deactivation and arousal.

Overall, our participants seem to have been asleep, and unaffected by their environment. Thus, the question arises as to whether they might have entered a sort of psychological and physiological hibernation, to reduce their discomfort. These results are consistent with the idea that survivors seem to cut themselves off from the world they find themselves in, while being very aware of their actions. Could this be a form of adaptation to a new environment that is difficult to grasp? Our participants' senses seem to have been sharpened, and they were ready to deal with any eventuality. Recently, a new type of adaptation has been identified during wintering in Antarctica. Sandal et al. (2018) pointed out that individuals may enter a state of psychological hibernation as an adaptation to stress during polar wintering. This type of coping has been corroborated by other authors, and it is associated with a depletion in resources as the coldest period approaches, and the reconstitution of resources in the second half of the stay (Basner et al., 2014; Palinkas & Suedfeld, 2021; Zimmer et al., 2013). Although this strategy seems to be influenced by environmental conditions, it may not necessarily involve a long period of isolation and confinement, if environmental demand is sufficiently high. Not all outcomes in extreme environments are pathogenic; they can also be salutogenic, as revealed by a substantial body of literature (Basner et al., 2014; Guly, 2012b; Kanas et al., 2013; Martin et al., 2019).

Turning to cognitive aspects, survival at sea challenges both cognitive performance and the integration of sensory information. Survival was found to have a deleterious impact on performance, and thus decision-making. Reaction times increased after the experiment, indicating that alertness and vigilance functions were negatively impacted. Consistently, the reaction to difficulty threshold (in the MindPulse test) fell. This index appears to be a relevant measure when compared with real-life cognitive performance, as proposed by Suarez et al. (Suarez et al., 2021). This result seems to go hand-in-hand with an increase in the number of errors linked to the introduction of a second choice in the Go/noGo task. One hypothesis is that survivors lose cognitive flexibility, becoming less able to adapt to stressful and/or challenging situations. This is problematic, as humans are required to perform complex cognitive functions in extreme environments. In this context, Martin et al. (2019) note that the severity and duration of exposure to an extreme environment are linked to both the degree of cognitive impairment, and task complexity.

Temperature is another factor that is known to impact cognitive performance (Hancock et al., 2017; Lieberman et al., 2009; Smith & Barrett, 2018; Vrijkotte et al., 2016), and it has been negatively associated with performance in increasingly complex tasks (Hancock et al., 2007). Stress should also be considered. While a certain degree of stress can enhance performance, it can become deleterious and even invalidate the benefits of training when environmental demand exceeds the individual's internal resources (Motley, 2005). It is therefore fundamental that, in addition to training, crews can increase their personal resources and cognitive reserves. A better understanding of this interaction would make it possible to predict and counteract poorer performance in extreme environments.

Several effects are observed at the sensory level. Participants' perceptions of their tactile environment degraded, and they were less able to feel their body move in space, based on subjective sensorial acuity assessments. The hedonic value of smell increased. The hearing assessment showed that the threshold for auditory discomfort fell in both the right ear (at 1000 Hz, 2000 Hz, 4000 Hz, and 8000 Hz) and the left ear (at 500 Hz and 8000 Hz). Furthermore, hearing discomfort increased at 500 Hz for the left ear, and at 4000 Hz for the right ear.

These findings are consistent with those reported in a study of a nuclear submarine patrol, which found a decrease in the LDL at 500 Hz, 1000 Hz, 2000 Hz and 8000 Hz in the right ear (Lefranc et al., 2021; Le Roy et al., 2023). Similarly, space mission research has shown greater hearing loss in the left ear than the right ear among male astronauts (Reschke et al., 2014). It appears that the left hemisphere is better-able to filter out cross-noise than the right hemisphere, and thus that the right ear plays an important role in hearing processing (Prete et al., 2016; Saliba et al., 2011). Humans can cope with an emergency at sea if they are properly informed and trained (Anderson, 1978; Cross & Feather, 1983; Leach, 1986). The reduction in the LDL observed in our study suggests that participants may have paid more attention to the surrounding noise and/or lowered their noise tolerance threshold. It is not possible to comment on the hypothesis of sensorineural or attentional adaptation. Leach (1986) emphasizes the need for training to support appropriate responses to environmental demands (especially emergencies), which should be focused on removing fear and enabling automatic processes. Cross and Feather (1983) report that individuals who are less familiar with emergency procedures exacerbate the problem during an emergency at sea. Our observed reduction in the LDL needs to be related to the detection of useful sounds in survival situations before we can determine if it constitutes a beneficial adaptation or not. The observed tendency to an increase in the subjective perceptual exteroceptive modulation could contribute to the reduction in the LDL that we found for both ears at several frequencies.

Proprioception was deeply impacted during our experiment. Effects were observed in both closed and open eyes conditions for postural stability, ellipse surface, speed, logarithm, viscoelasticity of the posterior leg muscles, and CoP respiratory shift. Previous studies in ICE/EUE have reported similar results. Simulations of the environmental conditions experienced onboard a submarine (Cymerman et al., 2002), and during an SSBN patrol (Ferragu, 2019) suggest that there are subjective symptoms, and disturbances in postural stability. Moreover, a study in the NEMA habitat analog found that crew members had not recovered their pre-mission sensorimotor performance after several weeks (Bloomberg et al., 2015b). Postural stability and control involve high-level cognitive functions, such as attention to bodily cues that provide information about the body’s orientation in space (Amboni et al., 2013). Our results highlight that cognitive performance, especially high-level cognitive functions, were impaired. In this context, earlier work (Ouaknine, 2009) demonstrates that the slope of the line that connects the local CoP to the mean location index provides clinical information about potential pelvic torsion; at the same time, factors associated with postural instability have been shown to be associated with reduced sensation (Lord et al., 1991).

Several of our sensory indices suggest hypersensitivity. It is reasonable to assume that a sensory deficit, based on the disturbed integration of sensory information, contributed to the decrease in proprioceptive abilities. It is also worth noting that the environmental reference frame changed during our study. Participants were not on dry land for five days. During this time, they moved to the rhythm of the waves, which constituted their new environment. Studies of space missions have found that astronauts require 3–4 days to accustom their vestibular system to the new environment (Lackner & Dizio, 2006; Reschke et al., 2017). During the first 12 hours following their return from a space mission, and for several weeks after landing, they continue to have difficulty standing when performing dynamic head tilts (Clément et al., 2020). Black et al. (1995) found that astronauts needed 4–8 days to recover from postural instability. These events are driven by vestibular modifications.

4.2. The challenge of recovery

The survival experience had significant impacts that persisted into the recovery period. Many individuals did not recover, or even deteriorated further. Sleep, mood, and sensory discrimination seem to have been most impaired.

Beginning with sleep, most individuals recovered their ability to fall asleep and wake up and resumed their former bedtime habits. This result may reflect a gradual return to real life, and more comfortable sleeping conditions. It may also be in line with the rebound that is described after sleep deprivation, which is an important adaptive behavior (Suchecki et al., 2012). It would be interesting to evaluate the profile of individuals who had a sleep rebound, to better-understand interindividual variation in stress due to survival at sea. At the same time, our participants experienced ongoing fatigue and exhaustion that was directly related to their time at sea, along with other factors of daily life. Sleep is fundamental to optimal functioning and good health, and studies have reported that sleep deprivation may impair both performance and health (Medic et al., 2017; Orasanu & Lieberman, 2011; Orzel-Gryglewska, 2010), especially among healthcare workers [Kaliyaperumal et al., 2017; Lockley et al., 2007; Weinger & Ancoli-Israel, 2002). Nevertheless, sleep deprivation is a persistent feature of extreme space or analog environments (Kanas et al., 2007; Orasanu & Lieberman, 2011; Pattyn et al., 2018). Van Dongen et al. (2003) showed that just four days of sleep deprivation was associated with cognitive impairment, notably working memory, attention, language skills, and communication.

Participants seem to have improved their physical fitness at recovery. The desire to work disappeared, as did thymia, reflected in lower activity and arousal levels. They also perceived more stress and were more sensitive to distractions, linked to difficulties in focusing their attention. These results may be linked to the impact of returning to an active life, and greater difficulty dealing with day-to-day stressors. This may extend the time needed for recovery, which is even more costly.

Some functions did not return to their baseline level, notably sleep (e.g., difficulty in waking-up, tiredness), balance and coordination, interoception (attention and awareness to body sensations), and sensory distortions (increased distractibility due to difficulties in focusing attention, vulnerability to perceptual abnormalities during periods of fatigue and stress, over-inclusion or hyperattention). Survivors remained sleep-deprived and did not recover their pre-experiment level. They also failed to recover awareness of their body sensations. Earlier results have shown that poor sleep quality is associated with poorer interoceptive awareness in people with mental disorders (Ewing et al., 2017). More precisely, sleep disorders could inhibit interoceptive abilities in neurotypical individuals (Arora et al., 2021).

Thus, it is unclear whether participants in our experiment increased their sensory filtering threshold upon their return to real life, and whether they remained in a state of hypersensitivity to sensory stimuli. Our results are consistent with those found in the literature. A study onboard an SSBN patrol reported decreased sensory discrimination and interoceptive awareness during recovery for participants with a non-adaptive profile compared to those with an adaptive profile (Lefranc et ., 2021). In the latter study, groups were determined using the cardiac biosignal, specifically parasympathetic and cardiac flexibility components. Finally, after a 520-day Mars simulation, crew members took part in a parabolic flight campaign, which found increased cortisol levels compared to the control group (Bersenev et al., 2013).

Several earlier studies have identified neurovestibular impairment, especially head-trunk coordination, or motion perception (Bloomberg et al., 2015b; Clément et al., 2020; Stahn & Kühn, 2021).

Our participants reported less negative affect at recovery compared to baseline. Two hypotheses may be advanced: (1) there was a gradual exit from their state of hibernation; or (2) the finding is evidence of an ability to put the experience into perspective. While emotional hibernation seems to be a characteristic of survival in space, the return to Earth seems to be associated with difficulties with emotional and sensorial responses (Yuan et al., 2019). For example, Šolcová et al. (2014) showed that crew members changed how they felt and regulated their emotions during the Mars 500 mission. Change in how emotions are expressed may be a manifestation of the adaptation process after time spent in extreme environments (Moraes et al., 2020; Nicolas et al., 2013). Overall, a lack of recovery can lead to psychological and behavioral disorders and compromise an individual's ability to adapt to usual environmental stresses for at least a few days. Nevertheless, very few studies have focused on recovery, while it is an essential component for understanding human functioning *in situ* (Bersenev et al., 2013; Bloomberg et al., 2015b; Cannon, 1929; Clément et al., 2020; Nicolas & Gushin, 2015; Nicolas et al., 2015).

The exploration of analogous terrains has introduced new opportunities to better-understand interactions between psychological, physical, cognitive, and sensory levels, and support an integrative and global view of adaptation mechanisms. This understanding is essential to help crews to continue to function efficiently during their mission, and to recover after it. Knowledge of the immediate effects of extreme conditions on cognitive functioning, and the long-term neuropsychological consequences of exposure is essential to understand both how to train individuals for these demanding situations, and the tools that should be provided. Future space missions to Mars will require crews to maintain optimal performance, despite the physical and psychological stressors imposed by environmental and professional demands. Moreover, we must prepare for potential space shuttle accidents during future long-term missions. It will be fundamental to keep in mind that having survival skills is important but, most of all, having the will to survive is essential.

5. Limitations

This study has several methodological shortcomings that are inherent to the ecological environment. The first is the small sample size, and an imbalance between male and female, and right- and left-handed subjects. Studying such a population is complex, both in terms of time constraints, and access to infrastructure and personnel (i.e., operational constraints, attendance). Both the scientific team and participants must be flexible in order to run such an experiment. Secondly, our results are not reproducible beyond the specific experimental conditions and cannot be generalized. Simulated survival at sea is an EUE and can be seen as an analog of an accident in space. Thirdly, psychological and interoceptive data (i.e., collected through questionnaires) are subjective measures. Intelligent sensors would provide more objective measures of subjects' adaptation to extreme environments. Fourth, while the PolarH10 belt is currently the best tool to accurately record RR intervals with the minimum of artifacts given our environmental constraints, the device cannot replace an ECG. Finally, as differences were detected for the two groups of participants (i.e., lifeboat and life raft) at baseline (i.e., except for proprioception), we pooled results for the analysis. However, seven people onboard the lifeboat were right-handed (70%) and three were left-handed (30%), whereas 10 were right-handed (91%) and one was left-handed (9%) on the life raft. This distribution may explain the differences at baseline in proprioception.

6. Conclusion

The present study is one of the first of this magnitude to demonstrate the impact of five days of survival at sea on individual adaptation. Our results are unequivocal. The harsh environment affected the majority of the organism's components. At psychological and physiological levels, individuals seem to enter a state of hibernation to reduce the body's operating costs. At the sensory level, participants entered a state of hypervigilance and hypersensitivity to stimuli in the external environment. Conversely, cognitive performance significantly deteriorated, and proprioception was deeply impacted. These results raise the question of the potential risks during future long-term space missions, when accidents may occur. Individuals will have to maintain their cognitive performance at a high level to be able to respond to environmental demands and survive. If they cannot, the risks will be too great. Finally, a better understanding of response mechanisms in a survival situation is crucial to be able to identify and develop countermeasures that can maintain the adaptive capacities of crew members.

7. References

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8. Supplementary Material

Cognition. Executive speed (p = .627, BF_{10} = .320), total errors to overall accuracy (p = .324, BF_{10} = .448), outliers to accuracy (p = .615, BF_{10} = .323), and reaction time range (p = .264, BF_{10} = .508), did not change. Results did not change for executive speed (p = .627, BF_{10} = .320), errors to choice on precision (p = .111, BF_{10} = .919), and reaction time range (p = .348, BF_{10} = .430) for the orientation/ selective attention function. Similar results were found for the number of total errors (p = .324, BF_{10} = .448), categorization speed (p = .964, BF_{10} = .288), number of inhibition errors (p = .573, BF_{10} = .264), and anticipation errors (p = .838, BF_{10} = .293) for the executive control function.

Vision. Natural (p = .188, BF_{10} = .510), short (p = .569, BF_{10} = .265) and long (p = .105, BF_{10} = .772) distance accommodation did not change.

Hearing. Change in the LDL at frequencies: 500 Hz (p = .187, BF_{10} = .437) for the right ear; and 1000 Hz (p = .209, BF_{10} = .516), 2000 Hz (p = .166, BF_{10} = .564), and 4000 Hz (p = .275, BF_{10} = .450) for the left ear, were not significant.

Hearing. Change in the LDL at frequencies: 500 Hz (p = .299, BF_{10} = .378), 1000 Hz (p = .129, BF_{10} = .520), 2000 Hz (p = .149, BF_{10} = .464), and 8000 Hz (p = .484, BF_{10} = .315) for the right ear; and 2000 Hz (p = 1.000, BF_{10} = .272), 4000 Hz (p = .233, BF_{10} = .411) and 8000 Hz (p = .484, BF_{10} = .311) for the left ear, were not significant.

Olfaction. No significant change was found for detection (p = .149, BF_{10} = .466) and identification (p = .120, BF_{10} = .934) post-experiment. For the other senses, no significant differences were found for taste (p = .283, BF_{10} = .388), or vision, including min (p = .569, BF_{10} = .000), max (p = .105, BF_{10} = .772) and distance accommodation (p = .188, BF_{10} = .510).

Proprioception. In the open eyes condition, none of the following differences were significant: weight distribution in the left foot (p = .291, BF_{10} = .382), weight distribution at front in the left foot (p = .082, BF_{10} = .658), weight distribution in the right foot (p = .563, BF_{10} = .254), speed variance index (p = .405, BF_{10} = .314), slope (p = .215, BF_{10} = .465), average left to right (p = .325, BF_{10} = .357), AN02 left to right (p = .412, BF_{10} = .349), AN02 front to rear (p = .539, BF_{10} = .261), and LFS (p = .100, BF_{10} = .804) . In the closed eyes condition, none of the following differences were significant: weight distribution for the left foot (p = .821, BF_{10} = .236), weight distribution at front for the left foot (p = .321, BF_{10} = .360), weight distribution at rear for the left foot (p = .476, BF_{10} = .288), weight distribution for the right foot (p = .611, BF_{10} = .257), weight distribution at front for the right foot (p = .639, BF_{10} = .236), weight distribution at rear for the right foot (p = .490, BF_{10} = .251), speed variance index (p = .264, BF_{10} = .407), slope (p = .404, BF_{10} = .315), average left to right (p = .656, BF_{10} = .250), slope in degrees (p = .531, BF_{10} = .273), AN02 (p = .203, BF_{10} = .723), and LFS (p = .268, BF_{10} = .403).

Body awareness. None of the body awareness (p = .640, BF_{10} = .247) or dissociation (p = .506, BF_{10} = .262) indices changed significantly.

HRV. LF (p = .157, BF_{10} = .696), the LF/HF ratio (p = .201, BF_{10} = .487), the SD ratio (p = .873, BF_{10} = .230), $\alpha 1$ (p = .355, BF_{10} = .309), $\alpha 2$ (p = .251, BF_{10} = .420), and sample entropy (p = .653, BF_{10} = .250) did not change significantly.

Interoception. None of the differences in the other interoceptive measures reached significance: noticing (p = .096, BF_{10} = .820), not distracting (p = .360, BF_{10} = .298), not worrying (p = .330, BF_{10} = .319), emotional awareness (p = .741, BF_{10} = .174), self-regulation (p = .839, BF_{10} = .159), and trusting (p = .690, BF_{10} = .184).

Thymia. No significant differences were detected for: tenseness (p = .146, BF_{10} = .593) and calmness (p = .780, BF_{10} = .168).

Emotion. Positive affect did not change significantly (p = .239, BF_{10} = .407).

Sleep quality. Sleep onset (p = .255, BF_{10} = .387) changed significantly.

Perceptual energy. Neither of the following measures: morale (p = .441, BF_{10} = .256) or mood (p = .597, BF_{10} = .241) changed significantly.

Sensory discrimination. Over inclusion (p = .101, BF_{10} = .483) did not change significantly.

Sensory evaluation. None the following measures changed significantly: olfaction (p = .326, BF_{10} = .322), taste (p = .129, BF_{10} = .654), posture (p = .961, BF_{10} = .144), touch (p = .108, BF_{10} = .748), vision (p = .771, BF_{10} = .221), and hearing (p = .888, BF_{10} = .152).

Subjective exteroceptive acuity. None of the following measures changed significantly: vision (p = .123, BF_{10} = .412), hearing (p = .528, BF_{10} = .313), olfaction (p = .666, BF_{10} = .221), and taste (p = .916, BF_{10} = 233).

Synthèse des résultats principaux

L'étude RAD'LÔ avait pour objectifs : (1) évaluer l'impact d'une simulation de survie en mer sur les réponses psychologiques, cognitives, physiologiques et sensorielles ; et (2) mesurer la récupération dans les jours suivants la situation de survie.

Nos résultats soulignent qu'en cas de situation de contraintes aigues pendant 5 jours, comme c'est le cas lors de cet exercice de survie en mer, la majorité des réponses de l'organisme est affectée. Celles-ci continuent même de se dégrader après la fin de la situation de survie. L'équipage voit une diminution du fonctionnement de l'ANS associé à un état que l'on pourrait qualifier « d'hibernation psychologique ». On observe également une charge mentale et physique importante et une hypervigilance/hypersensibilité sensorielle. Par conséquent, plus l'environnement est extrême, plus la demande environnementale est importante, et plus les moyens pour s'adapter coûteux pour l'organisme afin de retrouver un état homéostasique.

Cette étude s'inscrit dans un environnement combinant non seulement l'isolement et le confinement mais aussi l'inhabituel et l'extrême mis en œuvre par un exercice. Les résultats obtenus sont probablement des réponses minimisées d'une situation réelle de survie. Ils soulignent une variabilité inter-individuelle des réponses au stress qui est informative pour mieux appréhender la préparation des équipages aux situations critiques, qui seront inévitables et de durée non prédictible lors des LDSE.

L'étude des réponses de l'organisme à ces deux environnements de simulation (ANTIDOTE et RAD'LÔ) ont permis de cartographier les réponses psychologiques, physiologiques, cognitives et extéroceptives en situation de stress aigu, dans un cadre ICE et EUE marqué par l'incertitude. Il convient également de considérer que les risques d'incidents inhérents à la mission surviendront chez des individus évoluant depuis un certain temps dans un environnement de routine. Cette « routine spatiale » qu'elle concerne les déplacements entre bases-vie ou le stationnement en base-vie est en soi un environnement de contraintes qui engage les réponses d'adaptation.

Les deux études précédentes ont étudié des situations critiques particulières que pourraient avoir à expérimenter les astronautes dans les missions futures de longue durée. Les deux études suivantes s'inscrivent dans le cadre plus normalisé d'une mission de longue durée : le trajet pour rejoindre la base et le séjour sur la base-vie.

Nous nous intéressons en premier lieu au trajet. Le « vaisseau », véritable capsule, constitue *per se* un stresseur environnemental non négligeable des vols spatiaux. L'enfermement dans un espace restreint a montré des répercussions négatives sur l'adaptation, notamment psychologiques. Le sous-marin, notamment le sous-marin nucléaire lanceur d'engin (*sub-surface ballistic nuclear-powered missile submarines*, SSBN) acteur clé de la dissuasion nucléaire française, représente un des analogues les plus approchant par le nombre de stresseurs qu'il partage avec les missions spatiales. Il offre un modèle pertinent pour étudier comment un groupe d'individus sélectionnés et experts évolue dans une ambiance ICE. Pour autant, ce rapprochement n'a que peu été effectué, possiblement en raison des équipages plus importants en nombre (i.e., environ 110 marins), des durées de mission du sous-marin contraintes par la stratégie de la dissuasion nucléaire française (i.e., environ 80 jours), et de la difficulté d'accès à cet environnement que ce soit pour mener des recherches, comme pour y récupérer des données ou encore pour obtenir des informations relatives au contexte de la mission et au fonctionnement du groupe.

Nous avons choisi d'étudier précisément l'impact d'une mission dans cet analogue en ciblant le mécanisme physiologique d'adaptation que nous avons ciblé dans les études précédentes, celui de la réponse de l'ANS, et particulièrement l'activité vagale. Ce système, indexé par la variabilité de la fréquence cardiaque (*heart rate variability*, HRV), est proposé comme un marqueur de la qualité de la régulation du stress (pour méta-analyse, Kim et al., 2018a). Pour autant, sa prise en compte en milieu ICE a encore peu été exploré. La littérature a également mis en évidence l'importance des afférences autonomes participant à l'intéroception dans l'élaboration d'une réponse comportementale adaptée puisque celles-ci déterminent la branche de l'ANS qui sera activée pour faire face à la situation (Porges, 2007, 2009). L'intégration des informations intéro-extéroceptives est de ce fait essentielle dans la régulation des processus d'adaptation, notamment émotionnels. Cependant, aucune étude ne s'est attachée à étudier l'impact d'une patrouille de sous-marin sur les réponses psychologiques, physiologiques et extéroceptives en fonction de l'activation de l'ANS parasympathique (*parasympathetic nervous system*, PNS) au repos des sous-mariniers.

L'étude avait pour objectifs principaux : (1) mieux comprendre l'impact des environnements ICE/EUE sur les changements physiologiques, sensorielles, psychologiques au cours d'une patrouille de sous-marin en fonction du fonctionnement de la HRV avant le départ en mission ; et (2) comparer les impacts en fonction du fonctionnement du PNS au repos avant le départ.

Nous posons l'hypothèse que la patrouille entraîne une diminution du fonctionnement psychologique et extéroceptif de l'équipage. Également, les sous-mariniers ayant un fonctionnement du PNS faible devraient être ceux pour lesquels l'impact au décours de la patrouille est le plus délétère et la récupération, la moins efficiente au retour de la mission ; contrairement à ceux ayant un fonctionnement du PNS élevé.

Cardiac Biosignal in Confined Nuclear Submarine Patrol:

Heart Rate Variability a Marker of Adaptation

Publié[10]

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Abstract

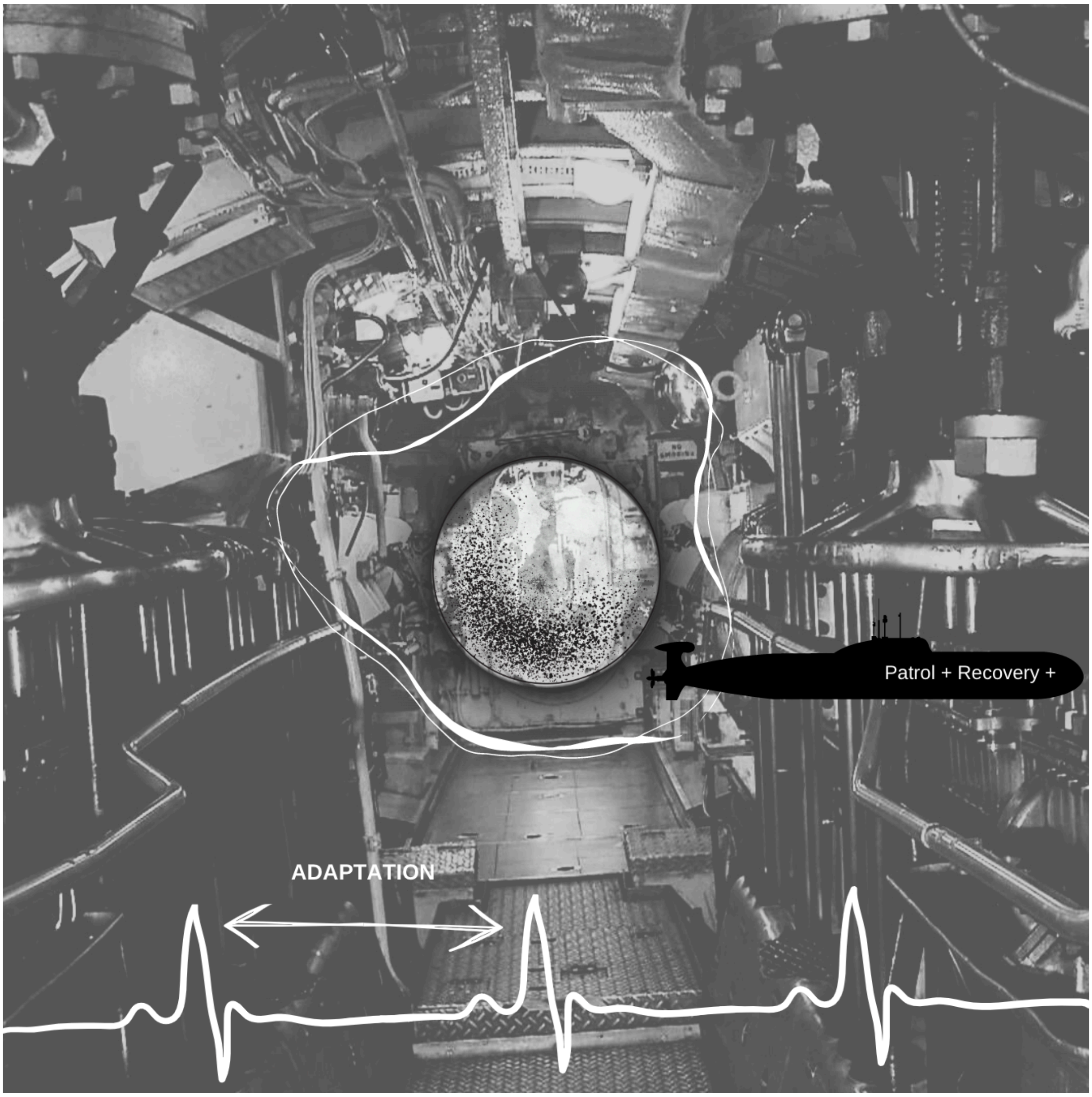
Introduction. Extreme and unusual, and isolated and confined environments (EUE/ICE) are characterized by unique sensory stimulation. They are known to adversely affect human psychology and physiology, and threaten the outcome of spatial, polar, or submarine missions. This exploratory study evaluates the negative impact of a submarine patrol on the psychological and sensory performances according to heart rate variability (HRV).

Method. Nineteen submariners were classified into high parasympathetic activity (HPa) and low parasympathetic activity (LPa) groups using their pre-patrol parasympathetic level. The impacts of the mission on emotional health, interoception and exteroception were evaluated at baseline, twice during the patrol, and once at recovery one month later. Emotional health was assessed using the scale of positive and negative experience (SPANE) questionnaire. Interoception and exteroception were evaluated using other questionnaires and sensorial assessments, respectively.

Results. In all cases, no significant inter-group difference was found for emotional health. Exteroceptive and interoceptive functioning was better among the HPa group compared to the LPa group, both during the patrol and at recovery. HRV measures for the HPa group indicated a more adaptable profile, marked by greater cardiac vagal tone during the patrol and at recovery.

Discussion. Our results are the first to highlight the impact of physiological differences in HRV profile on adaptability in an ecological constraint environment. Such research would open perspectives for submariners' preparation, but also the design of countermeasures that bring us closer to Mars.

Figure 20
Graphical abstract SSBN



Keywords

Adaptation, Cardiac biosignal, EUE/ICE, Exteroception, Interoception, Submarine

1. Introduction

« *For years, I've been wondering what could happen to nuclear submarines when they dive and disappear from the surface of the earth for months, without a trace. No one really knows where they are* » (Guy Hamilton).

The operational capacity of a sub-surface ballistic missile nuclear submarine (SSBN) relies on crews being able to maintain their capabilities at the highest level, in a situation that combines the characteristics of both an isolated and confined environment (ICE), and an extreme and unusual environment (EUE). ICE/EUE are typically experienced by astronauts, polar winterers, or submariners in the course of their work. They are marked by extreme climates, danger, limited facilities and supplies, separation from loved ones, and the requirement to interact with other human beings [1]. Recently, Ramachandran et al. [2] characterized these environments as situations that place high demands on the individual's physiological, emotional, cognitive, and/or social resources. Historical data from research stations in Antarctica and space missions suggest that prolonged periods of social and sensory monotony can have a negative impact on human functioning, notably psychosocial health [3–9], cognition [10,11], poorer emotional regulation, and increased vulnerability to negative emotions [12]. Empirical evidence suggests that these constraints are linked to the passage of time there seems to be specific, critical phases during missions in ICE/EUE [13–20].

The submarine environment is one of the most stressful, and psychologically demanding forms of military service. Personnel are both isolated and confined, a situation that highlights issues of privacy, the space each has in the environment, and potentially a source of conflict on board between crewmembers [21,22]. Individuals onboard a SSBN live side-by-side with a nuclear weapon, and the fear of potentially lethal damage. This situation can upset the balance between the demands of the environment, and the resources mobilized by individuals, leading to changes in the individual–environment relationship. As Rivolier et al. [23] note, with respect to the extreme nature of certain situations, « the individual is placed in circumstances with intense emotional potential or requiring an adaptive response, an adjustment, which he experiences as beyond his means ». However, stressors related to submarine conditions have been relatively little studied. One example is Earls [24], who defined the multifaceted stressors experienced by a submariner on patrol. These stressors are linked not only to environmental constraints (isolation, confinement, absence of day/night cues, monotonous routine, lack of communication with the outside world, extended separation from family members), but also their professional duties (standing watch, the operational cycle, the hostile environment, the presence of nuclear weapons) [25–33]. The SSBN patrol routine places great demands on submariners. This naturally stressful environment should lead to a better understanding of their inter-individual differences in dealing with stress.

Furthermore, the literature underlines the inter-individual variability on stress response among healthy subjects. Physiological stress has a functional cost, and the study of heart rate variability (HRV) has become widely-accepted as an objective marker of an individual's response [34]. Indeed, environmental responses are consistent with changes in activity in the sympathetic, parasympathetic, and enteric components of the visceral motor system that govern the smooth muscles, the heart muscle, and the glands. These systems play a major role in sympathovagal balance and, thus, contribute to the maintenance of adaptive homeostasis with inter-individual differences [35]. This balance was mainly evaluated by short-term, temporal metrics from the variation between each consecutive heartbeat. Thus, change in HRV may reflect body's and mind's resistance to a psychological or physical stressor, and cardiac biosignals could be an index of the adaptability of the heart to changing environmental conditions. HRV has been validated as an objective method for evaluating stress [36, 37]. This physiological signal was integrated in the ICE/EUE environment [38], and into military research [39, 40]. However, assessments of the relationship between stress and HRV are diverse. Currently, the literature highlights the role of the parasympathetic activity as a brake on stress [35,41–44], especially parasympathetic activity has been associated with a vulnerability to depression [44]. Literature [45, 46] noted that the root mean square successive difference (RMSSD) is one of the most useful HRV index for the activity of the parasympathetic nervous system and the quality of the stress response.

The stress response is integral to living organisms and is characterized by interactions with the environment. The individual is transformed by interactions with the World [47] and this enaction is mediated by interoception [48]. The latter constantly provides the subject with information to maintain homeostasis in response to the demands of the living world from exteroception, which provides the subject with information about the state of the environment. Together, both interoception and exteroception emphasize the internal representation we have of our body in relation to the environment [49]. The perception of the body actively contributes to the adaptive response of subjects in environments with physical and psychological constraints [50]. The response relies on sensory integration, which refers to the process by which the brain receives a message through the senses and transforms it into an adapted behavioral response. It is defined as the appropriate use of sensory inputs from the body's [51] receptors and, according to Ref. [52], involves two main modalities: ensuring survival (modulation), and relating to the environment (discrimination). These two functions are essential to the individual's adaptation to his or her environment, and they are modulated by proprioceptive, interactive, and exteroceptive sensory receptors [53]. Although the literature underlines the role of sensory perception in stress adaptation, emotional functioning, and social relationships, the role of sensory functioning is mainly studied in the elderly, and children with neuropsychiatric problems [54–57]. Exteroceptive and interoceptive perception remain little-explored in the healthy subject. However, recent exploratory works point to an alteration in sensory perception in SSBN submariners [58,59] that could involve the submarine sensory environment such as a monotony in exteroceptive stimulations resulting from a lack of sunlight, confined space, a lack of sensory variation and novelty. For example, the auditory environment always remains at a high decibel level, the vision of distance is constrained by the corridors, or meals, although particularly taken care of by the cook, include less and less fresh food as the patrol goes on. Kubzansky [60] defined the main dimensions of under- and over-stimulation, which include intensity (loudness), and diversity (variation in stimulation and patterning, or the elimination of patterned visual information) as stressors. It is considered that poverty in sensory stimulation can lead to a decline in brain plasticity [61,62], with an effect that is even more marked than over-stimulation. The sensory over- and under-stimulations that exists during a submarine patrol lead us to question their role in the well-known deleterious effects on physical, emotional, and cognitive health via mechanisms that affect sensory integration, and lead to inappropriate stress responses.

Furthermore, there are individual differences in human adaptation to ICE/EUE environmental stressors [43–47,63]. Some evidence suggests that the human adaptation in stressful environment may be strongly dependent on interoceptive pathways which lead to the moment-to-moment awareness of bodily functioning [64–66]. Whatever how exteroception and interoception interact on each other to guide adaptation, interoceptive ability is considered to shape the ability to respond to external stimuli over the long term [67,68] by orchestrating regulatory responses both at a conscious level, through emotions and feelings, and at the autonomic level [69]. Especially, a greater HRV measured using RMSSD and interoception is associated with better emotion regulation [66], as adjusted behavioral outcomes [70,71]. In this context, extreme situations through the exteroceptive characteristics may disrupt adaptation in those individuals who are least prepared for dealing with changes inherent to the submarine environment. Thus, our understanding of adaptability could be enhanced by focusing on a protective HRV activity and validate its use on this ecological context. However, no study has been done to explore the use of cardiac biosignal on board a SSBN. The only study available to date concerns a submarine experimental facility simulating conditions some meters below sea level [72].

This exploratory study aims to better understanding the impacts of ICE/EUE environments on sensory and emotional changes over the cycle of a submarine patrol according to HRV functioning before the patrol. We put forward three hypotheses. First, the patrol will deteriorate the psychosensory functioning of submariners over time. Secondly, the patrol environment will have a more deleterious impact on the psychosensory functioning of subjects with low parasympathetic HRV activity (the LPa group), compared to those characterized by high parasympathetic HRV activity (the HPa group). Thirdly, recovery will be less efficient among the LPa group compared to the HPa group. This article explores the relevance of its use in such an environment.

2. Materials and methods

2.1. Design

This prospective cohort exploratory study was conducted with the crew of the French SSBN Le Triomphant, which was scheduled to make a 60 to 80-day patrol in autumn/winter 2017–2018 (precise SSBN mission dates are classified). An application to run the study was submitted to the Committee for the protection of persons southeast VI (Clermont-Ferrand) and received a favorable opinion on September 15, 2017 (IDRCB: 2017-A01329-44).

2.2. Participants

Participants were 29 male submariners belonging to the crew of the SSBN Le Triomphant. They were recruited by the ship's doctor, who presented the study, its objectives, and constraints in a briefing during preparations for the mission. Inclusion criteria were that subjects were deemed fit for submarine navigation (French Decree of July 18, 2014) under current Armed Forces Health Service regulations (IM n◦600). All subjects had a normal audiogram, indicating good hearing.

2.3. Data collection

2.3.1. Self-administered questionnaires

A 16-item socio-biographical questionnaire (SbQ) was used to collect standard socio-demographic data such as age, health status, specialty in the navy, pace of work, number of diving hours, and hobbies. The 12-item scale of positive and negative experience (SPANE) was used to assess subjective feelings of well-being, based on how frequently they were felt over the previous four weeks [73]. The 32-item multidimensional assessment of interoceptive awareness (MAIA) assessed interoceptive awareness. It is divided into eight, sub-factors that measure, among other things, awareness of uncomfortable, comfortable, and neutral body sensations, the response to sensations of pain and discomfort, the ability to regulate attention to body sensations, and awareness of mind-body integration [74]. The 36-item sensory gating inventory (SGI) evaluated abnormal perceptual salience as four sub-factors: perceptual modulation, over-inclusion, distractibility, and sensory fatigue [75].

2.3.2. Extrasensorium

2.3.2.1. Vision

Vision was assessed by the Parinaud scale (the French equivalent to the Jaeger chart), which measures the natural accommodation distance (from the tip of the nose to the reading surface, measured with a tape measure) at which the subject holds a text to read it comfortably. Paragraphs of text are written in decreasing font size. The recommended reading distance to test visual acuity is 33 cm, with a tolerance ranging from 30 to 35 cm. Luminance was controlled with a luxmeter to ensure that the lighting environment was the same for all subjects.

2.3.2.2. Hearing

The loudness discomfort level (LDL) is commonly used to test hearing in patients who may be intolerant to sound. In subjects with normal hearing, it is evaluated using pulsed, ascending tones at frequencies of 500 Hz, 1000 Hz, 2000 Hz, 4000 Hz and 8000 Hz, until the individual reports a feeling of discomfort. The instructions that are given to subjects is determinant in the type and quality of the response. In our study, volunteers were placed in a quiet room and told: « You will hear sounds that will become louder. Please raise your hand when the sound becomes unbearable, the sound will stop immediately. The aim of the test is to identify when the intensity leads to discomfort, and not to distinguish if the sound is loud or weak. For example, the sound might be loud, but not uncomfortable ». About 90% of subjects reported discomfort at intensities ranging from 90 to 105 db. Stimuli were recorded and presented using the Electonica 600 M system. Each stimulus was presented for approximately 2 s, with an interval of approximately 1 s between each presentation, until the subject reported discomfort.

2.3.2.3. Olfaction

The European test of olfactory capabilities (ETOC) assesses olfactory sensitivity. Individuals are asked to select a bottle (there are 16 sets of four bottles) that contains a specific odor (discrimination) and state the nature of this odor (identification). Participants were also asked to evaluate the hedonic value of the detected odor. The odor threshold was evaluated with the Sniffin' Sticks test (48 sticks, divided into 16 sets of three bottles). This validated test is commonly used to evaluate olfactory function in healthy individuals, and in individuals with a poor sense of smell. The odor to be detected is the same throughout the test, but the concentration gradually increases. This makes it possible to detect the individual's perception threshold. Two versions of the test are available: 2-phenylethanol evaluates perception of odors considered to be pleasant, and n-butanol evaluates detection of unpleasant, dangerous odors. As these odors may be present onboard an SSBN, their detection is essential for mission safety.

2.3.2.4. Proprioception

Proprioception was assessed using postural stability tested with a stabilometric static platform (Stabilotest). Subjects were asked to stand for 1 min with their eyes open, and

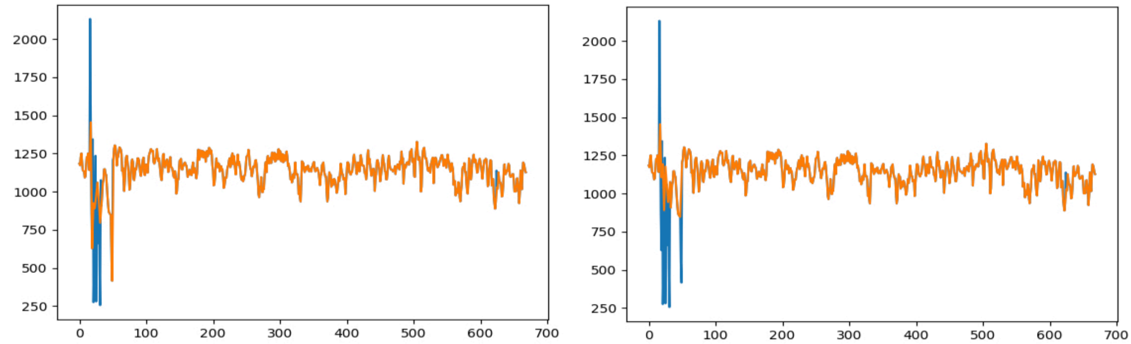
1 min with their eyes closed. Among the numerous metrics regularly used to characterize postural stability [76,77] in the literature, we assessed the most frequent metrics: weight distribution between left and right foot, sway length, standard deviation along the sagittal (Antero-posterior) and frontal (Medio-Lateral) directions, 90 confidence elliptic area, and slope its principal axis, centre of pressure (CoP) mean velocity, and its variance.

2.3.3. HRV

Heartbeat interval data (RR) were recorded for a 10-min period, with subjects in a sitting position, using an electrocardiogram (ECG), at a sampling frequency of 250 Hz (Codesna, Physioner). Two electrodes were attached to each wrist with a clamp. These sensors picked up electrical signals from the heartbeat and sent real time information to Physioner software, via Bluetooth. The HRV analysis was done according to the guidelines reported in Ref. [78], considering possible circadian variations, using the PyHRV python library [79]. The following data were also recorded: weight, height, waist-to-hip ratio, smoking habits, most recent alcohol intake (>24 h), most recent caffeinated (coffee/tea) intake (>1 h), most recent meal (>2 h), most recent physical activity (>12 h), and quality of sleep on the day of the experiment and the preceding day.

Raw ECG data were filtered between 3 and 45 Hz using a finite impulse response band-pass filter. The order of the filter was set at 75 (0.3 times the sampling frequency). R peaks were automatically detected using the BioSPPy python library based on 10 min ECG recording [80]. Once the signal is filtered, a Hamilton segmentation is performed, followed by an R-peak correction with a tolerance set to 0.05. The validity of R wave detection was manually examined to ensure correct detection. If an ECG sequence was overly noisy when visualizing the superposition of all QRS complex, a time interval was manually removed to improve data quality. RR intervals were automatically detected with the hrvanalysis module using linear interpolation, and manually corrected for artifacts and ectopic beats. In the case of outliers, RR intervals considered to be correct were changed manually (Fig. 1).

Figure 1
RR intervals (in ms) before and after manual correction of the detection interval considered to be correct

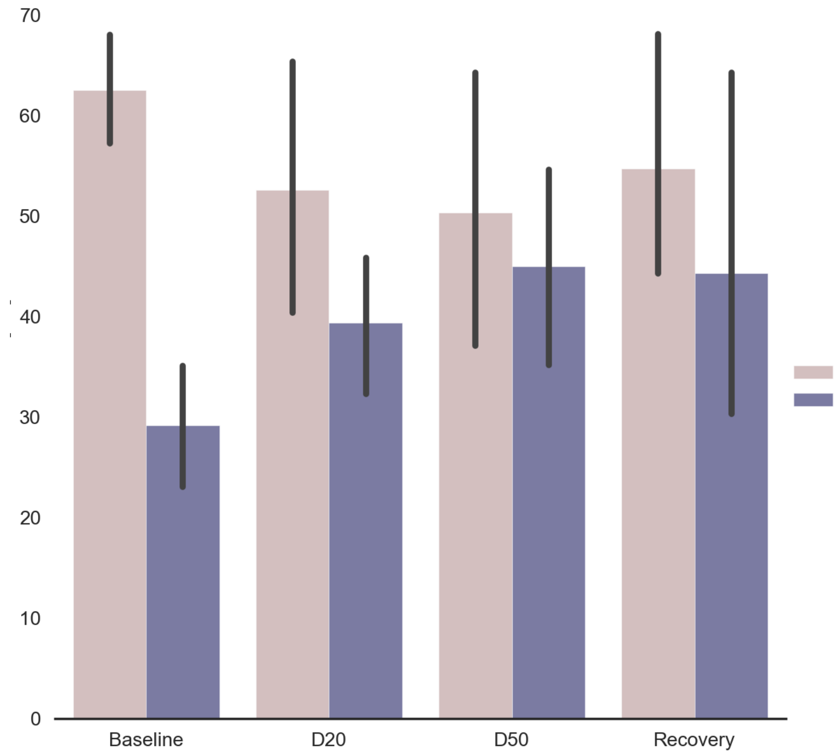


Time domain analysis. Time domain HRV metrics included mean RR (mean interbeat interval), SDNN (standard deviation of the normal-to-normal RR interval), RMSSD (root mean square of successive differences between adjacent RR intervals), and pNN50 (percentage of adjacent NN intervals that differ from each other by more than 50 ms).

Frequency analysis. Frequency domain HRV metrics complemented time domain metrics and include the properties of oscillatory components in heart rate dynamics. Spectral density was estimated using Welch's method: low frequencies (LF, sympathetic and parasympathetic activity) in the range 0.04–0.15 Hz, high frequencies (HF, parasympathetic activity) in the range 0.15–0.4 Hz.

The median, a validated method to separate a population on RMSSD, was used to estimate two groups [81]. Given the small number of submariners inherent to the ecological environment, we use a widely accepted statistical method to split our sample in two profiles, while having an equal distribution between them. The choice was also to simplify the representation of the results through a clear categorization of groups by limiting the number of possibilities. This is achieved using artificial categorization [82]. At baseline, the first group exhibited a high parasympathetic HRV activity (HPa profile), characterized by a predominance of parasympathetic nervous system (PNS) activity at rest, compared to the second group (LPa profile). This identified two groups, differentiated on their physiological functioning. Even if the frequency HRV variables depend on the respiratory rate, we evaluate the impact of HRV profiles on the frequency domain [83]. Participants were seated during the entire ECG recording. Therefore, breathing is not expected to have a major impact. Fig. 2 presents the RMSSD evolution between groups throughout the patrol.

Figure 2
Profile's RMSSD evolution throughout the patrol



2.4. Experiment

Psychological and physiological data were collected in four sessions: a few days before the patrol left (baseline), at two times during the patrol (D20 and D50), and after a month of vacation that followed the end of the patrol (recovery). They were collected identically in an ecological environment: for D20 and D50 onboard the SSBN; and for baseline and recovery, at the patrol's departure point. The chronology of baseline measurements was adapted to operational constraints. As far as possible, data were recorded during the same morning or afternoon time slot. The scientific team was blinded to participants and data anonymized. Each subject completed the series of questionnaires at baseline. The SbQ characterized the population. Mental health was assessed by the SPANE, sensory functioning by the SGI, and interoceptive functioning by the MAIA. HRV was recorded, along with sensoria. All measures (except the SbQ) were repeated at D20, D50 and recovery (Fig. 3). To minimize the experimental load for each participant, and time constraints for the onboard doctor, each subject was randomly allocated to one of two groups (A or B) for the comparison of emotional health, sensory, and stress levels (Table 1).

Figure 3
Experimental design. Symbols shown in squares summarize the variables collected (questionnaires, HRV, sensoria)

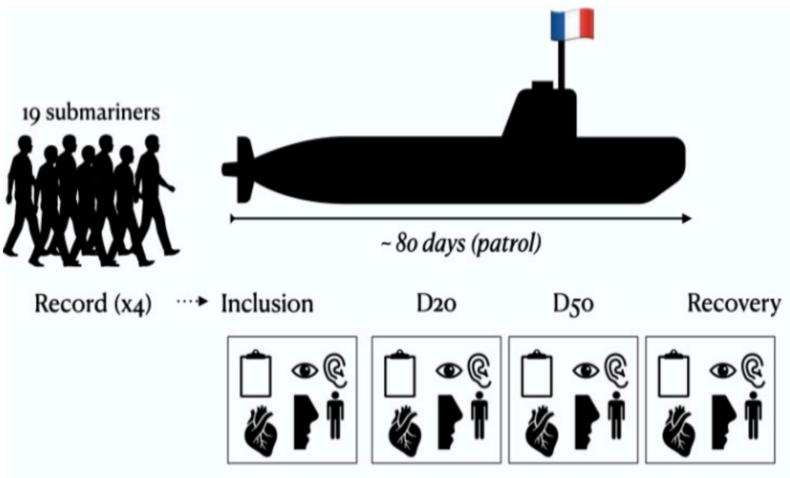


Table 1
Randomized distribution of subjects into groups

Group A (n=10)	Group B (n=10)
Hearing	Vision
Sense of smell 2-phenylethanol	Sense of smell n-butanol
Interoception	Interoception
SPANE	SPANE
HRV	HRV

*One participant was included in both groups.

2.5. Data analysis

Data analyses were performed with python scripts (Python Software Foundation, Wilmington, v3.8) and RStudio (RStudio, Boston, v1.2 5001). Stress adaptability was evaluated using one baseline HRV metrics, the RMSSD, linked to parasympathetic activity. Thus, the median was used to distinguish our population. In this sense, we consider the hypothesis that we have different groups based on their parasympathetic activity at rest. Statistics were computed for all outcome measures. Statistical analyses assessed the impact of the patrol on submariners. The Shapiro–Wilk test was used to determine whether data were normally distributed. Both nmle library and nparLD library (F1 LD F1 design) were used depending on the data distribution to analyze the repeated measurements (four times) taken from both HRV groups to explore significant differences. Time effects post hoc tests were performed with the nparLD package and Group x Time effect post hoc tests were performed with the Mann-Whitney-Wilcoxon. For significant analyses, the effect sizes were reported. Depending on the distribution of the data, we used the partial eta squared and the relative treatment effect (RTE). The partial eta squared indicates a small ($\eta^2 = 0.01$), a medium ($\eta^2 = 0.06$) or a large effect ($\eta^2 = 0.14$). The RTE indicates no effect (RTE = 0.5), a tendency for participants in a subgroup to score at least as high as a randomly chosen individual from the whole sample (RTE >.5), the probability of a randomly chosen individual from the subgroup having a higher score than an individual randomly chosen from the whole data (RTE >.7), the probability of a randomly chosen individual from the entire subgroup having a lower score than a randomly chosen individual from the subgroup (RTE = .2).

For all analyses, statistical significance was set at $p < .05$. $0.05 < p < .07$ was considered as evidence of a trend.

3. Results

3.1. Population demographics

Out of the 29 submariners recruited, ten dropped out due to time constraints (difficulties and challenges in maintaining the pace of the experiment on board the SSBN and after the patrol's return). This group had a mean age of 29.73 years (±6.94), and a mean weight of 75.78 kg (±8.77). The length of service of the crew on an SSBN is 7312 (±7151) hours. 12 participants (63.15%) have a morning chronotype and seven (36.84%) an evening chronotype. 15 submariners are in couple (78.94%) and four (21.06%) are single. Eight (42.10%) have experienced at least one stressful family event and five (26.31%) at least one stressful professional event. 15 (21.06%) submariners are smokers and 18 (94.73%) are right-handed. The addictive intensity evaluation questionnaire (AIEQ) that assess addictive physical actuality practices reports on average 39.94 (±10.05). Finally, eight (42.10%) are on off-shift (i.e., day shift) while 11 (57.89%) are on watch shift (i.e., day or night shift). They are homogeneous as only one subject had no previous experience on board a SSBN. All submariners perform physical activities in daily life. Table 2 and Table 3 summarizes the socio-demographic differences between submariners.

Table 2

Sociodemographic data (n=19)

Sociodemographic variables	Data
Age	29.73 ± 6.94
Weight	75.78 ± 8.77
Morning/ evening chronotype	12 (63.15%) / 7 (36.84%)
Family situation (couple/ single)	15 (78.94%) / 4 (21.06%)
Stressful family event (>1/ none)	8 (42.10%) / 11 (57.89%)
Stressful professional event (>1/ none)	5 (26.31% / 14 (73.68%)
Smoker/ non smoker	4 (21.06%) / 15 (78.94%)
Right-handed	18 (94.73%)*
Addictive physical practices	39.94 ± 10.05
Length of service on an SSBN (hours)	7312 ± 7151
Off watch (day shift) / watch shift (day/ night shift)	8 (42.10%) / 11 (57.89%)

*One participant did not declare his laterality.

Table 3

Psychosensory differences between HRV profiles at baseline

	Lifeboat (N = 10)	Life raft (N = 11)	*p*-value*
SGI			
Perceptual modulation	2.10 ± .71	1.22 ± .79	.02
Over inclusion	2.80 ± .84	1.92 ± 1.00	.05
Fatigue stress modulation	2.64 ± .82	1.79 ± 1.00	.06
MAIA			
Trusting	3.10 ± 1.32	4.14 ± .69	.04

*p-value used in the analysis of group effects. Means and standard deviations are shown for each variable.

3.2. Baseline HRV profiles and psychosensory differences

Table 3 presents a summary of the psychosensory differences for each profile. No inter-group differences were observed for sociodemographic data (notably, stressful life events), SPANE scores, or the exteroceptive assessment (vision, hearing, proprioception). With respect to sensory functioning (SGI), a significant effect was found for perceptual modulation, with higher scores in the LPa group compared to the HPa group ($p = .02$). Scores for over inclusion were also significant again, the LPa group scored higher than the HPa group ($p = .05$). Trends were observed for fatigue stress modulation ($p = .06$); in both cases, the LPa group scored higher than the HPa group. With respect to interoceptive functioning (MAIA), a significant effect was observed for trusting; the LPa group scored lower than the HPa group ($p = .04$).

3.3. Impact of HRV profile on psychosensory and HRV functioning during the mission

A summary of the results is presented in Table 4. With respect to the mental health assessment (SPANE), a significant time effect (ATS (df = 2.77) = 9.63, $p < .001$, RTEs = 0.70, 0.38, 0.37 for baseline, D50 and recovery) was observed for negative emotions. Score at baseline is higher compared to D50 ($p < .001$) and recovery ($p < .001$). For positive emotions, a significant time effect (ATS (df = 2.17) = 26.33, $p < .001$, RTEs = 0.66, 0.39, 0.30, 0.64 for baseline, D20, D50 and recovery) was found. Score at baseline is higher compared to D20 ($p < .001$) and D50 ($p < .001$). Also, score at D20 is lower compared to recovery ($p < .001$). Score at D50 is lower compared to D20 ($p = .03$) and recovery ($p < .001$). No difference was observed between groups.

Table 4

Analyses for the interactions between group and time on psychosensory functioning among the submarine experiment

	Baseline		D20		D50		Recovery		*p*-value*
	LPa	HPa	LPa	HPa	LPa	HPa	LPa	HPa	
SPANE									
N[b]	2.40 ± .737	2.59 ± .571	2.16 ± .593	1.99 ± .543	1.87 ± .429	1.80 ± .340	1.83 ± .488	1.80 ± .533	.000
P[b]	3.93 ± .802	4.15 ± .453	3.13 ± .846	3.54 ± .471	2.64 ± 1.07	3.22 ± .568	3.75 ± .876	4.15 ± .543	.000
MAIA									
N[b,c]	3.42 ± .541	2.88 ± .907	2.91 ± .665	3.29 ± 1.02	2.45 ± .970	2.72 ± 1.13	2.70 ± 1.04	3.17 ± 1.11	.02
ND[b,c]	2.87 ± .724	2.40 ± .520	2.09 ± .674	2.32 ± .580	1.67 ± .544	2.26 ± .547	2.23 ± .876	1.59 ± .465	.006
NW[b]	3.90 ± .903	4.03 ± .539	3.06 ± .645	3.04 ± .568	3.53 ± .632	3.15 ± .444	3.57 ± .545	2.89 ± .898	.000
AR[b]	2.67 ± .863	3.05 ± .827	2.37 ± .869	2.85 ± .801	1.94 ± 1.20	2.71 ± .909	1.94 ± 1.21	2.76 ± .606	.008
SR[c]	2.65 ± 1.20	2.71 ± .150	2.38 ± .922	2.87 ± .796	2.72 ± 1.16	2.92 ± 1.07	1.92 ± 1.53	3.25 ± .740	.05
T[a]	3.10 ± 1.32	4.14 ± .697	3.40 ± 1.47	4.24 ± .675	3.00 ± 1.45	4.30 ± .611	3.00 ± 1.66	3.89 ± 1.18	.04
Hearing									
RE 500 Hz[b,c]	93 ± 4.47	94 ± 5.48	90 ± 11.70	91 ± 2.24	91 ± 8.94	100 ± 0.00	88 ± 10.40	94 ± 5.48	.01
Proprioception									
YFwLF[b]	49 ± 3.72	48.40 ± 3.05					49.60 ± 4.85	49.90 ± 2.10	.001
YFwRF[b]	51 ± 3.72	51 ± 2.28					50.40 ± 4.85	50.30 ± 2.06	.01
YFwLFf[b]	24.90 ± 5.65	25.80 ± 6.16					25.30 ± 2.43	26.10 ± 3.92	.01
YOfrA[b]	30.50 ± 8.14	29.40 ± 10.70					22.10 ± 9.53	20.50 ± 14.50	.000
YOsv[b]	110 ± 210	48.80 ± 28.90					32.90 ± 17.70	27.10 ± 22.20	.02
HRV									

Mean RR[a]	794 ± 80.90	1006 ± 127	850 ± 119	897 ± 171	877 ± 111	946 ± 160	844 ± 75.70	961 ± 105	.01
SDNN[a,c]	55.10 ± 16.00	86.90 ± 16.70	63 ± 18.70	71 ± 21.70	72.20 ± 23.10	71.70 ± 23.60	70.10 ± 33.50	76.40 ± 28.90	.01
RMSSD[a,c]	29.20 ± 10.20	62.60 ± 8.71	39.40 ± 11.18	52.60 ± 20.80	45 ± 16.20	50.40 ± 21.90	44.30 ± 30	54.70 ± 20.20	.000
pNN50[a,c]	9.67 ± 8.08	42.40 ± 7.77	19.30 ± 11.40	34.60 ± 21.00	24.50 ± 15.30	30.90 ± 21.00	20 ± 20.60	34.60 ± 18.00	.002
LF[c]	1186 ± 677	2247 ± 1364	1565 ± 1172	1217 ± 670	2418 ± 1522	1307 ± 869	2656 ± 3300	1834 ± 1329	.01
HF[a,c]	411 ± 294	1587 ± 680	692 ± 361	1317 ± 810	899 ± 624	1125 ± 1015	1178 ± 2029	1236 ± 920	.007

Note. LPa = low parasympathetic with less unpredictability and flexibility cardiac biosignal; HPa = high parasympathetic with greater unpredictability and flexibility cardiac biosignal; N = negative emotions; P = positive emotions; N = noticing; ND = not distracting; NW = not worrying; AR = attention regulation; SR = self-regulation; T = trusting; LE : left ear; RE = right ear; YFwLF = weight distribution on the left foot in the closed-eye condition; YFwRF = weight distribution on the right foot in the closed-eye condition; YFwLFf = weight distribution on the left foot at the front in the closed-eye condition; YOfrA = average front/rear weight distribution in the open-eye condition; YOsv = speed variation in the open-eye condition.

[*]*p*-value used in the analysis of effects. Means and standard deviations are shown for each variable. All variables were recorded at four times, appart from proprioception where baseline and recovery were collected. Only significant interactions were reported ($p < .05$).

[a] Significant group effect.

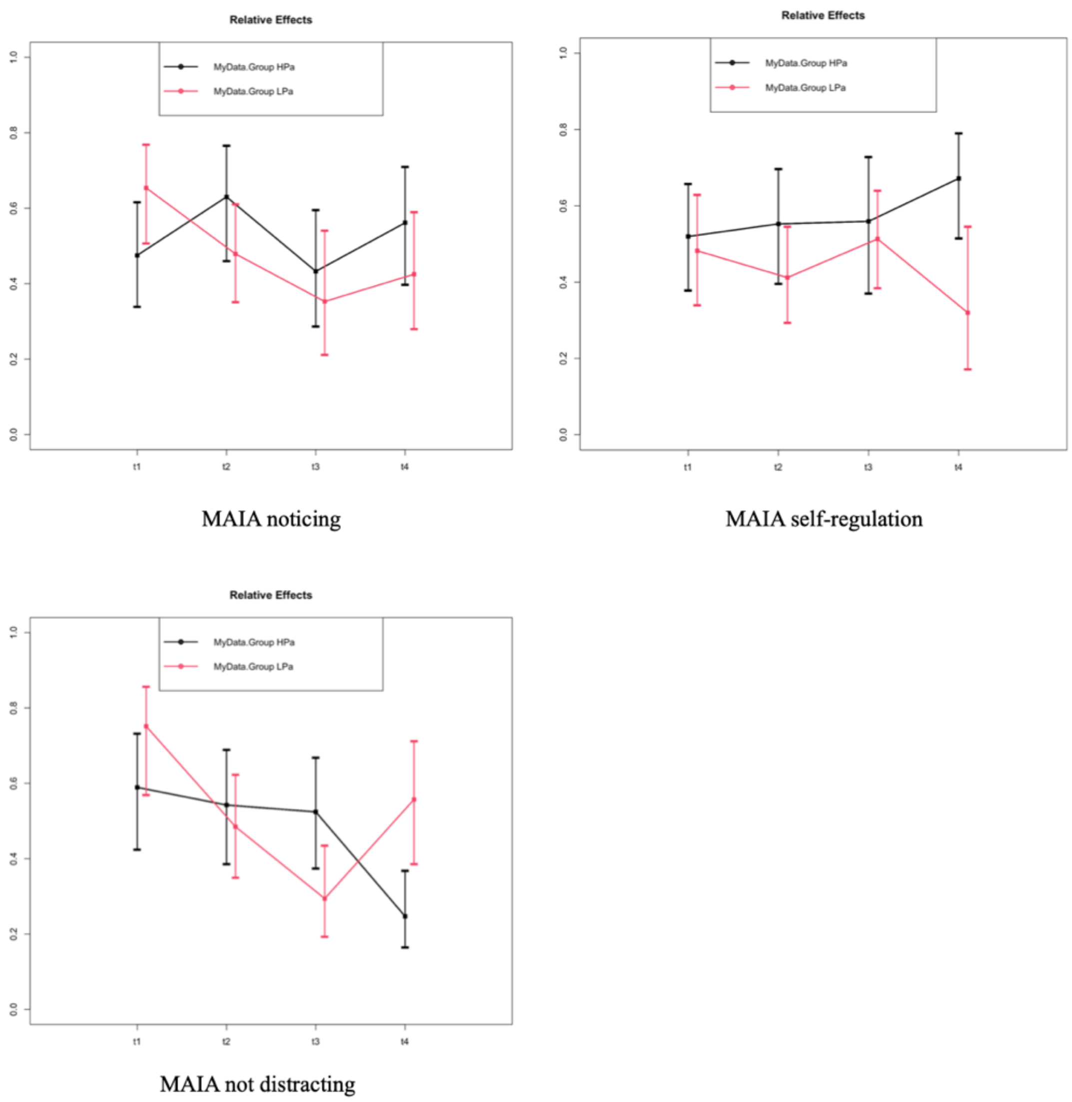
[b] Significant time effect.

[c] Significant group x time effect.

With respect to the interoceptive functioning (Fig. 4), significant effects were found for the following variables. For noticing, a significant time effect (ATS (df = 2.71) = 3.39, p = .02, RTEs = 0.55, 0.39 for D20 and D50) and group x time effect (ATS (df = 2.71) = 3.22, p = .02, RTE = 0.35 for LPa at D50) were found for noticing. Score at D20 is higher compared with D50 (p = .04). For LPa, score at baseline is higher compared to D50 (p = .03). For not distracting, a significant time effect (F (3, 51) = 6.19, p = .001, η^2 = 0.27 90% [0.08, 0.40]) and group x time effect (F (3, 51) = 4.63, p = .006, η^2 = 0.21 90% [0.04, 0.35]) were observed. Score at baseline is higher compared with D50 (p = .006) and with recovery (p = .004). For LPa, score at baseline is higher compared to D50 (p = .001). For not worrying, a significant time effect (ATS (df = 2.63) = 8.22, p < .001, RTEs = 0.71, 0.35, 0.47 for baseline, D20 and D50) was found. Score at baseline is higher compared with score at D20 (p < .001) and at D50 (p = .007). For attention regulation, there is a significant time effect (ATS (df = 2.59) = 4.16, p = .008, RTEs = 0.60, 0.45 for baseline and recovery). Score at baseline is higher compared with score at recovery (p = .02). For self-regulation, a significant group x time effect (ATS (df = 2.90) = 2.58, p = .05, RTEs = 0.51, 0.67, 0.31 for HPa at baseline, HPa at recovery and LPa at recovery) was found. HPa have a lower score at baseline compared to recovery (p = .03). At recovery, HPa tends to have a higher score compared to LPa (p = .06). For trusting, a significant group effect (F (1, 16) = 4.57, p = .04, RTEs = 0.61, 0.39 for HPa and LPa) was observed. HPa group have higher score compared to LPa (p = .04).

Figure 4

HRV profile throughout the patrol on relevant interoception subfactors

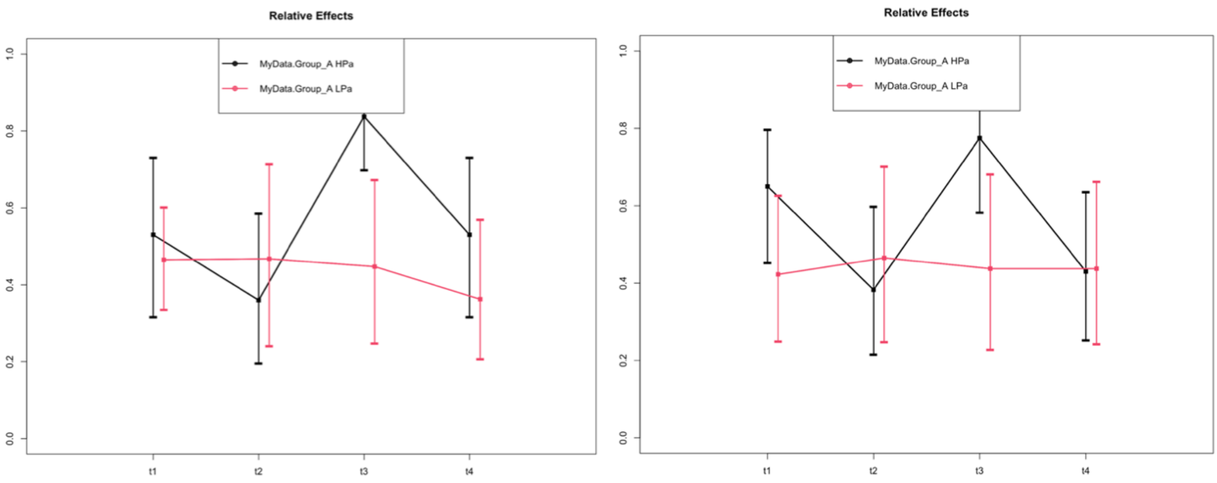


With respect to exteroceptive functioning, results found no effect for vision, taste, and olfaction. Effects were only found for hearing (Fig. 5) and proprioceptive assessments. At 500 Hz (left ear), a trend to a group x time effect (ATS (df = 2.38) = 2.58, p = .06, RTEs = 0.65, 0.38 for HPa at baseline and HPa at D20) was identified. LDL for HPa is higher at baseline compared to D20 (p = .04). At 500 Hz (right ear), a significant time effect (ATS (df = 2.42) = 3.58, p = .02, RTEs = 0.41, 0.64 and 0.44 for D20 and D50 and recovery) and a group x time effect (ATS (df = 2.42) = 3.79, p = .01, RTEs = 0.53, 0.36, 0.83, 0.53 for HPa at baseline, HPa at D20, HPa at D50 and HPa at recovery) were found. LDL at D50 is higher than score at D20 (p = .007) and score at recovery (p = .01).

LDL for HPa is higher at D50 compared to recovery (p = .02), lower at D20 compared to D50 (p = .005) and lower at baseline compared to D50 (p = .02).

Figure 5

HRV profile throughout the patrol on relevant LDL variables



LDL Right Ear   LDL Left Ear

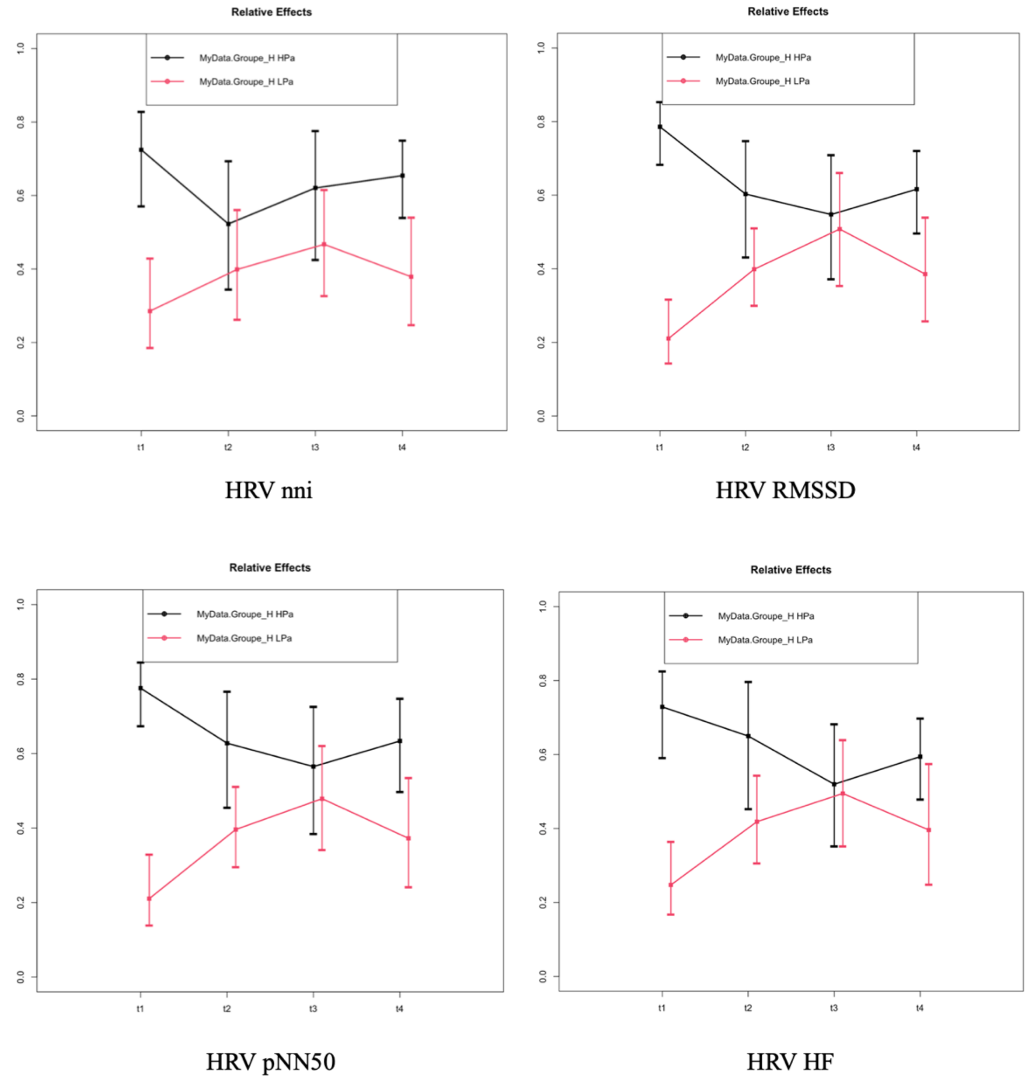
Significant effects were found for the proprioception assessment in the following measures. Concerning closed-eye conditions, a significant time effect (ATS (df = 1) = 10.49, p = .001, RTEs = 0.43, 0.55 for baseline and recovery) was found for weight distribution on the left foot. Score at baseline is lower compared with the score at recovery (p = .001). A significant time effect (ATS (df = 1) = 5.83, p = .01, RTEs = 0.55, 0.44 for baseline and recovery) for weight distribution on the right foot was identified. The score at baseline is higher compared with the score at recovery (p = .01). A significant time effect (ATS (df = 1) = 5.64, p = .007, RTEs = 0.41, 0.57 for baseline and recovery) was also observed for weight distribution on the left foot at the front. The score at baseline is lower compared with the score at recovery. Finally, a trend to a group effect (ATS (df = 1) = 3.77, p = .06, RTEs = 0.58, 0.40 for LPa and HPa) was found for the standard deviation of left-to-right weight distribution was observed. The score tends to be higher for LPa compared to HPa (p = .06).

Concerning the open-eye condition, A significant time effect (F (1, 17) = 22.48, $p < .001$, $\eta^2 = 0.57$ 90% [0.28, 0.73]) was identified for average front/rear weight distribution. The score at baseline is higher compared with the score at recovery ($p < .001$). A significant time effect (ATS (df = 1) = 4.92, $p = .02$, RTEs = 0.59, 0.40 for baseline and recovery) was identified for velocity variation. The score at baseline tends to be higher compared with the score at recovery ($p = .02$).

Turning to HRV (Fig. 6), a significant group effect (F (1, 13) = 8.22, $p = .01$, RTEs = 0.63, 0.38 for HPa and LPa) was found for mean RR. HPa exhibits higher mean RR compared to LPa ($p = .01$). For temporal HRV, a significant group x time effect (ATS (df = 2.23) = 4.12, $p = .01$, RTEs = 0.76, 0.30, 0.53, 0.54, 0.43 for HPa at baseline, LPa at baseline, LPa at D50, HPa at recovery and LPa at recovery) were observed for SDNN. HPa has a higher SDNN than LPa at baseline ($p < .001$) and recovery ($p = .01$). For LPa, SDNN tends to be higher at D50 compared to baseline ($p = .06$). A significant group effect (F (1, 15) = 9.09), $p < .001$, RTEs = 0.63, 0.37 for HPa and LPa) and a group x time effect (ATS (df = 2.77) = 6.42, $p < .001$, RTEs = 0.78, 0.21, 0.60, 0.39, 0.54, 0.50, 0.61, 0.38 for HPa and LPa at baseline, HPa and LPa at D20, HPa and LPa at D50, HPa and LPa at recovery) were identified for RMSSD. HPa exhibits a higher RMSSD compared with LPa ($p = .008$). HPa has a higher RMSSD than LPa at baseline ($p < .001$). For LPa, RMSSD is lower at baseline compared to D50 ($p = .04$). LPa has a lower RMSSD than HPa at baseline compared to D20 ($p = .002$), D50 ($p = .02$) and recovery ($p < .001$). A significant group effect (F (1, 14) = 11.60), $p = .004$, RTEs = 0.65, 0.36 for HPa and LPa) and a group x time effect (ATS (df = 2.85) = 4.87, $p = .002$, RTEs = 0.77, 0.21, 0.62, 0.39, 0.47, 0.37 for HPa and LPa at baseline, HPa and LPa at D20, LPa at D50 and LPa at recovery) were found for pNN50. HPa exhibits a higher pNN50 compared to LPa ($p = .004$). HPa have a higher pNN50 compared to LPa at baseline ($p < .001$), at recovery ($p = .03$) and a trend at D20 ($p = .06$). LPa has a lower pNN50 at baseline compared to D20 ($p = .04$) and D50 (p = .04). For frequency HRV, a significant group effect (F (1, 15) = 6.24, $p = .02$, RTEs = 0.62, 0.38 for HPa and LPa) and group x time effect (ATS (df = 2.58) = 4.26, $p = .007$, RTEs = 0.72, 0.24, 0.64, 0.41, 0.59, 0.39 for HPa and LPa at baseline, HPa and LPa at D20, HPa and LPa at recovery) were found for HF. HPa have higher HF compared to LPa ($p = .02$). HPa is higher than LPa at baseline ($p < .001$) and D20 ($p = .05$). LPa has a lower HF than HPa at baseline compared to recovery ($p = .005$).

Figure 6

HRV profile throughout the patrol on relevant cardiac biosignal



4. Discussion

The aim of this exploratory study was to evaluate the impact of stress on the emotional health, biocardiac signal and sensory performance of submariners during an SSBN mission, according to two groups differenciated on their HRV baseline profile before the mission. To the best of our knowledge, this is the first study to characterize stress adaptation based on resting parasympathetic activity assessed using HRV at baseline on board a SSBN, a very specific environment. The strength of this study is that it was carried out with a very specific population in an environment that is no less specific. This is the reason why, on the one hand, the number of participants, even if it is correct given the subject of the study, remains low and leads us to take the results obtained with precaution, particularly as regards their generalization.

Our methodological approach is not innovative within the literature but validated to identify adaptation profiles based on resting parasympathetic activity assessed using HRV [81]. Also, the RMSSD reflects the modulation of cardiac parasympathetic activity [46, 84, 85]. The selected HRV features were the most representative in the literature and advised by the gold standard in terms of HRV analysis [78,86]. Therefore, linear measures allow the HRV to be assessed in terms of variability and baroflex function. Furthermore, these findings are coherent with research into the reciprocal connections between the heart and the brain [87]. The neurovisceral integration model developed by Thayer et al. describes interconnections between the prefrontal cortex and cardiac activity [88, 89, 50]. This model postulates that parasympathetic activity serves as an indicator of the effectiveness of these interconnections [90,91]. The authors argue that the higher the resting parasympathetic activity, the more adaptable the individual is of responding to environmental stimuli [90]. Specifically, self-regulation, greater behavioral flexibility and adaptability in a changing environment are associated with high vagal tone. Inversely, low vagal tone is associated with poor self-regulation environment and a lack of behavioral flexibility. Similarly, the biological functioning of the human organism is based on multiple reactions that involve numerous central and peripheral structures, which are themselves activated on multiple time scales. A high level of complexity in neurophysiological systems allows young and healthy individuals to respond with significant flexibility and robustness to different environmental stimuli, without disturbing their longer-term homeostasis [92,93].

We found no difference with respect to sociodemographic or psychological data for the two HRV profiles. On the one hand, this similarity at baseline may reflect a healthy, and rigorously selected population. On the other hand, the two groups differ with respect to sensory functioning. The HPa profile is consistent with higher sensory functioning (higher confidence in their interoceptive body sensations, and less perceptive distortion) compared to the LPa profile. More precisely, the LPa profile appears to be more sensitive to modulations in stimulus intensity, perceptual flooding, and anomalies in focal attention. There is a tendency to experience radial attention difficulties resulting from a low perception threshold, along with vulnerability to perceptual and attentional anomalies during periods of fatigue and stress. The literature highlights that interoception is a multidimensional construct that is involved in emotional regulation [94]. The link between high HRV and interoceptive awareness is becoming increasingly apparent [95]. Consistent with the literature, we found that baseline sensory

functioning was less efficient among the LPa group. Our results are in line with the neurovisceral integration model [87,34] and the polyvagal theory [96]. They suggest that unconscious perception of the internal environment implies parasympathetic afferents and regulation [97]. Also, they highlighted the relationship between parasympathetic dominance and greater interactive awareness in the HPa profile. Nevertheless, even if not significant, the measures of both LPa and HPa seems to overlap at D20 and D50 (Fig. 2). This is might due to the RMSSD of the LPa profile that improved over time. The LPa profile appears to be the one who benefit the most from the patrol regarding the RMSSD index. More precisely, our results suggest an impact of patrolling on the psychosensory functioning of submariners aboard an SSBN. They also highlight a different psychosensory functioning as a function of HRV profile (HPa versus LPa profile) at baseline. The latter suggests that adaptation to an extreme environment differs according to the cardiac profile of individuals.

4.1. Impact of SSBN patrol on psychosensory functioning of submariners

The time is an important factor in ICE/EUE environments. The patrol induces changes in emotional, interoceptive and hearing exteroceptive variables. Negative as well as positive emotions are higher at baseline. During the patrol towards recovery, both emotions decrease with the lowest level at D50. However, there were fewer negative emotions and higher positive emotions at the end of the patrol than at the beginning with increased positive emotions as the end approaches. This is due to the training phase that preceded the patrol as well as the preparations for the upcoming mission [62]. Also, the prospect of seeing the family again can have a life-saving effect on the mental health of submariners. Although the impact of the mission on emotions disappeared one month after the end of the mission, effects remain on psychosensory functioning. Interoceptive changes implied a decrease in noticing, not distracting, not worrying, and attention regulation, with the lowest scores at the D50. Furthermore, an increase in LDL is observed for the right ear at 500 Hz towards the end of the patrol, with the highest level at D50. A One month after the patrol, LDL returns to its baseline level. Altogether, these results indicate that the submarine patrol is to be considered as a challenging professional environment and that effects are maximum at D50. These findings are consistent with empirical evidence of the existence of specific critical phases during missions in ICE/EUE environments [98,99]. Time itself would be a source of stress, the intensity of which would vary among stages during the mission [13–16]. The cycling pattern [24] associated with the operational constraints are related to the winter-over syndrome [19]. There is a pattern of winter-over syndrome or seasonal affective disorder during a SSBN patrol, particularly for watchkeeping submariners [31] with interindividual differences [26, 58]. Moreover, symptoms seem to increase after the midpoint of the mission, with some reduction in symptoms toward the end [25]. This pattern is known as third-quarter phenomenon. The third-quarter phenomenon posits that any experience of a defined duration of stress is divided temporally into four quarters and that stress-related symptoms are most likely to appear in the third-quarter (between the midpoint and three-quarters mark) of that duration [20]. However, our evaluation of proprioception found an impact of the patrol on postural stability of submariners at recovery. These results can be compared to studies of elite soldiers, whose higher metabolic, cardiovascular and anxiogenic responses are associated with a significant loss of fine motor skills after combat maneuvers [100]. At recovery, the postural stability of submariners is poorer than at baseline for both groups. Impact of the patrol at recovery mainly concern weight distributions on the feet with more weight for the front of left foot associated with more weight at recovery. This is observed in both close-eye and open-eye conditions. This is associated with an impaired postural stability in the open-eye condition as suggested by the increased speed variation and ellipse surface, as the decreased slope of the ellipse surface principal axis. The postural stability and control involve high-level cognitive functions such as attention of bodily cues to inform about the body orientation in space [101]. Notably, body awareness is particularly engaged during quiet standing because spontaneous postural oscillations trigger low intensity bodily changes [102]. Furthermore, earlier work [103] demonstrates that the slope of the line that connects local pressure centers to the mean location index provides clinical information about potential pelvic torsion, and factors associated with postural instability have been shown to be associated with reduced sensation [104]. Simulations of the environmental conditions experienced onboard a submarine [105], and during a SSBN patrol [59] suggest that there are subjective symptoms and disturbances in postural stability. In our study, the SSBN environment seemed to be deleterious for both HRV profiles with a greater (negative) impact on the sensory and interoceptive functioning of the LPa group. Thus, the interoceptive degradation could play a role on the non-recovery of the submariners' stability one month after the end of the patrol.

Finally, these findings are in line with several studies that have identified emotional stability/instability as a factor that influences adaptability in ICE [106].

4.2. Impact of HRV profile in ICE environment

Also, the impact of the patrol differs according to HRV profile at baseline. First, the HPa exhibits the highest impact in most of the interoceptive subscores. Most relevant differences between groups are found at the last steps of interoceptive integration. Mehling et al. [74] developed a dimensional model of the interoceptive based on four steps. The first step is about the perceptions to note subtle changes in body processes according to emotional/physiological state. Then, the quality of attention without being distracted or worried focuses on the emotional reaction, and attentional responses to sensations. The third includes trust, in relation with awareness of bodily sensations. Finally, mind-body integration includes emotional awareness, self-regulation, and body listening. In line with this framework, HPa exhibited higher stability and quality of interoceptive trusting and mind-body integration compared with LPa group. Although further research is needed to better-understand how interoception functions [107], our results are in accordance with the literature highlighting the role of the quality of internal sensations for regulating stress adaptation [108] and emotional state [109]. These findings are coherent with the theoretical model of Thayer [87]. HRV, reflecting the central nervous system, is related to processes involved in interoception, notably through the anterior cingulate. This conception allows us to meet the environmental constraints, modulating our psychophysiological resources.

Furthermore, hearing adaptation as assessed by LDL is lower for HPa at 500 Hz, whatever the ear. The highest difference between group is at D50. The SSBN is characterized by a high level of environmental noise, but the exact noise in frequency and intensity is not a communicable data. While this auditory environment may explain the observed changes in discomfort thresholds, our results suggest that hearing adaptation is more effective in the HPa group than the LPa group. This observation highlights the enactive property of human environmental interactions and suggests that adaptive neuroplasticity is more effective in the HPa group. Neuroplasticity, the ability of the nervous system to adapt to environmental changes, is intrinsic to brain function and essential to homeostasis [110]. It characterizes the nervous system's modification and remodeling processes that are at work at any given time. The brain is constantly learning, and the changes that are induced interact with our daily actions, intentions, and motivation. Furthermore, the differences between HPa and LPa are found only for the right ear. In a recent, analogous study, Van Ombergen et al. [111] demonstrated the involvement of neuroplasticity in a space flight environment, and their findings address two questions raised by our study: why one ear was only affected. Most of our submariners were right-handed, while space mission research has shown greater hearing loss in the left ear than the right ear in male astronauts [112]. It also appears that the left hemisphere is better able to filter out cross-noise than the right hemisphere. Therefore, the right ear plays an important role in hearing processing [113, 114]. This cross-side lateralization could explain why right-handed people have higher LDLs. Further research is needed to better understand the mechanisms involved in adaptation, and why this adaptation is right-sided.

Interestingly, HRV changes differ during the patrol between the two cardiac profiles. To summarize the results, LPa exhibited less protective HRV activity in terms of temporal variables (SDNN, RMSSD, pNN50), and frequency variables (HF) with a high sympathetic level (LF) throughout the patrol. The maximum effect appears on D50 as suggesting by the third-quarter phenomenon [6].

Altogether, the findings of the patrol effects could indicate the ability for the HPa profile to be aware of their sensations and to consider them helpful in maintaining health and making decisions [44]. The HPa group is linked to parasympathetic activity and thus better protective HRV activity contrary to the LPa group. This distinction in physiological functioning continues throughout the patrol. These results are in line with the literature which highlights the impact of the environment on the processes of adaptation and management to stress [44]. Recently, the generalized unsafety theory of stress claims that the stress response is considered as default. Brosschot et al. [42] note « the stress response is a default response of the organism, and that it is the response the organism automatically falls back upon when no other information is available ». Submariners on board a SSBN live with nuclear arm and fear of lethal damage. Unsecure environment leads to stress response [41]. Thus, there is a challenging opportunity with HRV to better understand how modulation of the parasympathetic activity may deal with these situations and lead to adaptation.

4.3. Impact of HRV profile on psychosensory functioning on recovery

Submariners one month after the return from the artificial environment have not regained their initial ability to feel their body sensations. The deleterious effect of the patrol is particularly observed for the first steps of interoception (not distracting, and not worrying). A lower recovery is found for LPa compared to HPa, with main differences between the two groups for the last steps of the interoceptive integration (self-regulation and trusting).

In line with our hypothesis, HRV functioning remains better for the HPa group at recovery compared to the LPa group. A healthy subject is characterized by more complex behavior, associated with a neutral emotional valence [115]. However, on one hand the HPa group did not recover their overall cardiac biosignal at recovery. On the other hand, the LPa group was marked by an active recovery from the deleterious impact of the patrol on their physiological functioning. One explanation is that the parasympathetic function is more effective in the HPa group, through both a good perception of sensory information, and over-activation of the sympathetic nervous system. Recently, Gould van Praag et al. [116] investigated autonomic arousal and alterations of activation and functional connectivity within the brain's default mode network while participants listened to sounds from artificial versus natural environments. They highlighted an increase in parasympathetic activity (measured by HF) of participants in a natural environment. More precisely, they found that the displacement of peak high frequency HRV between conditions was correlated with baseline levels. Individuals with low baseline parasympathetic activity showed an increase, whereas those with a high baseline showed a relative decrease, in a natural environment. The latter results are in line with our findings. At recovery, submariners are in a quieter, natural environment, where the braking function of the parasympathetic system is less relevant. Our results suggest that the HPa group gradually becomes worn out during the patrol. Thus, LPa submariners benefitted most from recovery in terms of adaptation.

Finally, our study highlights the use of HRV as a marker of adaptability. This tool is an effective way to differentiate submariners in terms of their cardiac vagal tone profile. The impact of the SSBN patrol can be assessed with respect to groups distinguished by their HRV, which would help to inform future research directions. Such research is a priority, given the need to maintain the operational capability of submariners, while ensuring their emotional health and body homeostasis. These results also confirm the hierarchical levels highlighted by Thayer et al. in updating their model of neurovisceral integration through the integration of interoceptive and exteroceptive information in regulatory processes [117]. More recently, there has been an increased interest in the nonlinear HRV domain, as it is thought to be a marker of the brain's ability to respond appropriately to minor changes in environmental demands [118, 119]. Specifically, the nonlinear domain provides information about complex physiological processes that classical, linear HRV metrics are unable to capture (quantifying the fractal nature of time series). However, there is a lack of studies to validate the physiological changes of such cues and their interactions with the central autonomic nervous system. Future research should focus on physiologically validating the potential of these cues while adopting a consistent methodology to advance research on the potential of HRV, particularly to lead to quality adaptation of the individual. In recent years, new technologies and advances in medical research have highlighted the value of embodied virtual medicine [120], vagus nerve stimulation [121], and mindfulness [122] through modulation of the cardiac vagal tone. Future research should focus on these potential countermeasures to enhance parasympathetic regulation.

4.4. Limits

This exploratory study conducted in a confined SSBN environment has several methodological shortcomings inherent to experiments run in ecological conditions. The first key limitation is the small sample size. A study of such a population is complex, both in terms of time constraints and access to infrastructure and personnel (operational constraints, attendance). The mission of SSBN personnel is to contribute to the defense of the country through nuclear deterrence. However, the sum up of differences appears to be relevant refer to the observed size effects ranging from minor to high). Secondly, our results are not reproducible beyond these specific conditions, and cannot be generalized. The small number of participants may impact statistical power. However, in this type of environment, it is extremely complicated to recruit an ideal number of subjects considering: 1) there are not many submariners on board; and 2) participation is on a voluntary basis. Our results should be confirmed with a new patrol to increase the initial number of subjects. The SSBN shares the characteristics of the ICE/EUE and is defined by the equipment used by the French Navy. Thirdly, the sample population is limited to a young, male crew, who are in excellent physical and mental condition, due to a rigorous selection process. Fourthly, psychological and interoceptive data (collected through questionnaires) are subjective measures. The use of intelligent sensors would provide more objective measures describing subjects' physical, psychological, and physiological functioning. Fifth, the ECG signal was sometimes very noisy due to the sampling frequency of the device used. Data quality and stability require an efficient system to record the electrical activity of the heart. The sampling rate is another key parameter. 250 Hz is the recommended minimum, and 500 Hz is the recommended average. The Polar H10 belt is currently the best commercial tool to accurately record RR intervals, with the minimum of artifacts. Also, even if the HRV recording times between the ground and the patrol diverge, constituting a limit, we have the minimum time to be able to analyze the RR intervals. Finally, results on proprioception highlight the need for recording how postural stability changes throughout the patrol using more metrics for better understanding the interaction between the patrol and the effects on postural stability. Indeed, detecting subtle bodily changes is critical to orientate the whole-body segment relative to gravity and prevent falls. Also, we did not measure vitamin D, which is important in stress resilience, especially in individuals with limited access to daylight. This is something that will be considered in future studies.

5. Conclusion

HRV profile clustering distinguished two groups that were differently adapted to the constraints of an SSBN patrol. Our results are an encouraging foundation for future studies that seek to assess the impact of ICE/EUE using HRV. Although they need to be confirmed in a larger study, this work is currently underway. They underline the importance of offering specific support to submariners (less adaptable) to maintain their operational capability. Studying the impact of the ICE/EUE onboard an SSBN is a priority for the French General Staff and the Armed Forces Health Service. This line of research will feed into analogous environments including research bases in Antarctica, and manned space flight. Future research will, therefore, must focus on intelligent sensors that should be used to monitor the physiological responses of subjects as objectively as possible. These measures could be a key advance in proposing efficient countermeasures for parasympathetic regulation. The real challenge is to maintain the capacity of adaptation to the stress of the occupants of these extraordinary environments, because tomorrow we will float in space.

6. References

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Synthèse des résultats principaux

Cette étude conduite au décours d'une patrouille sur un SSBN avait pour objectif de mieux comprendre l'impact du trajet vers une base spatiale à bord d'un vaisseau caractérisé par un environnement ICE/EUE, sur les changements physiologiques, sensorielles, psychologiques au cours d'une patrouille de sous-marin, et ce en fonction du fonctionnement du PNS avant le départ en mission.

La distinction de deux profils de fonctionnement parasympathique avant le départ en mission a mis en évidence des différences dans les capacités adaptatives et de récupération au décours d'une patrouille de SSBN. Le fonctionnement parasympathique indexé par la HRV semble être un marqueur d'adaptation des individus en situation de contrainte.

De plus, les réponses psychologiques intéroceptives et les réponses extéroceptives ont montré une évolution au cours du temps avec les niveaux les plus faibles lors du dernier quart de mission. Ces résultats suggèrent un syndrome du troisième quart. Ce dernier a largement été décrit dans les environnements ICE/EUE mais son observation n'est pas retrouvée dans toutes les missions en environnement ICE/EUE. La question se pose de l'importance de ce syndrome lorsqu'il s'agit d'un trajet vers une mission habitée en suggérant que le début d'une mission habitée soit à gérer par des individus possiblement dégradés par le voyage.

Une des caractéristiques des LDSE est qu'elles ne s'inscriront pas dans le même repère temporel que les missions actuellement menées à bord de l'ISS. Si elles sont classiquement d'une durée de six mois, de plus en plus d'astronautes restent pour des durées supérieures sans excéder encore un an de mission en microgravité. Une mission vers Mars impliquera au minimum six mois de voyage ne serait-ce que pour le trajet aller. Il est raisonnable de se demander quel en sera le retentissement sur les réponses adaptatives. Le facteur temporel constituera en lui-même un impact majeur associé à l'ensemble des autres stresseurs déjà présents. Se posera alors la question de la capacité des équipages à durer dans un état opérationnel adéquat pour réussir la mission. Mener dans ce sens des expérimentations sur Terre pour mieux appréhender l'impact d'une longue durée de mission dans des conditions analogues est fondamental. Van Ombergen et collaborateurs (2020) ont publié une revue systématique de la littérature sur l'ensemble des études menées sur la station Concordia, connue pour être un analogue pertinent à ce que serait la vie sur Mars. L'Antarctique constitue un véritable laboratoire naturel depuis que l'International Geophysical Year y a lancé les programmes de recherche scientifique. Ces auteurs ont montré les effets pathogéniques de tels séjours sur les terres de glace. Cependant, récemment, de plus en plus de recherches mettent en évidence que des effets salutogéniques sont également observés dans un tel environnement. L'amélioration des conditions de vie sur les stations, ainsi que les facilités de communication pourraient en être deux hypothèses explicatives en ce qu'elle faciliterait une réalisation personnelle. La réalisation de soi renvoie au nombre d'astronautes qui rapportent des expériences positives hors du commun, voire mystiques, à vivre dans l'espace. De façon similaire, la mission Mars-500 qui s'est déroulée durant 240 jours dans les locaux de l'Institut des Problèmes Biomédicaux (Institute of Biomedical Problems) à Moscou (Russie) a constitué un lieu de recherche unique pour recueillir des données pour le vécu de longue durée en environnement de base spatiale. Pour autant, les données issues des articles publiés ne mettent pas en évidence de contraintes majeures sur la santé. Des explications en lien avec la santé peuvent également être proposées qu'il s'agisse de modalités de sélection plus adaptées pour cibler des professionnels dans un meilleur état de santé avant la mission et/ou d'un soutien médical sur base optimisé.

Les expérimentations publiées dans ces milieux s'attachent souvent à étudier un aspect de l'état psychologique (e.g., sommeil, humeur, émotions), physiologique (e.g., stress, digestion), biologique (e.g., stress, épigénétique), sensoriel (e.g., appétit) de manière isolée, sans apprécier sa dimension multifactorielle (i.e., ce point tend à changer ces dernières années avec la publication des travaux de Nicolas et collaborateurs, 2015 ; 2021 ; 2022) et sans étudier l'enjeu de la récupération. C'est dans ce contexte que nous avons mené une étude durant un hivernage sur la base française de Dumont d'Urville en Antarctique. Au regard du faible impact observé sur le fonctionnement des sujets de ces études, nous nous sommes également attachés à caractériser le profil le plus adapté à la mission.

L'étude ISHOW avait deux objectifs principaux : (1) investiguer l'impact d'un séjour d'un an en Antarctique sur les réponses psychologiques, physiologiques et sensorielles ; et (2) évaluer la récupération de cette expérience dans le post-immédiat, soit deux jours après le retour sur le Continent. Un objectif exploratoire visait à mieux appréhender l'impact de la qualité de la santé avant le départ sur les réponses pendant la mission et lors de la récupération en post mission immédiate.

Nous faisons l'hypothèse que les mois d'hiver et le dernier quart de la mission sont les plus impactant sur les réponses psychologiques, physiologiques et sensorielles. Enfin, la récupération deux jours après le retour ne devrait pas être suffisante pour que la majorité des réponses psychologiques et extéroceptives retrouve le niveau de départ. Enfin, nous posons l'hypothèse que l'impact de l'hivernage sera d'autant moins grand que le niveau de santé au départ est remarquable.

The right stuff:

Salutogenic and Pathogenic Responses Over a Year in Antarctica

En révision[11]

[11] Le Roy, B., Martin-Krumm, C., Rabineau, J., Jacob, S., Dupin, C., & Trousselard M. The Right Stuff : Salutogenic and Pathogenic Responses Over a Year in Antarctica. *Acta Astronautica*.

Abstract

Introduction. Since the first human reached the South Pole, many studies have been conducted to explore the impact of an isolated, confined, and unusual environment on human adaptation. They highlighted both negative and salutogenic effects on crews, despite an intensive medical and psychological screening. Although several studies have focused on adaptation in the polar regions, there are still some missing pieces to understand its mechanisms. Thus, the objectives of the study are (1) to investigate the impact of a one-year stay in Antarctica on psychological, physiological, and sensory responses; and (2) to assess recovery from this experience two days later.

Method. Seventeen healthy participants were recruited to stay one year at the French Dumont d'Urville station in Antarctica. Psychological, physiological, and exteroceptive responses were measured the day of the arrival on the station (baseline), during each quarter of the wintering season (M4, M7, M10, M12), and two days upon the return on the continent (D+2). Subjects were allocated to two groups according to their scores at the general health questionnaire at baseline: very limited or no existence of minor non-psychiatric or psychotic disorders (i.e., out of norm or HN) and standard values for non-psychiatric or minor psychotic disorders within the general population (i.e., ordinary range or OR).

Results. Results highlighted both an adaptative during the winter months and pathogenic states during the last quarter of the mission and at recovery (D+2). The analysis of OR and HN profile among overwintering highlights a decrease in psychosensory responses, and thus a decrease in adaptation.

Conclusion. One year in Antarctica do not longer produce harmful consequences on the winterers included in this study. Nevertheless, the general heath questionnaire range indicated two levels of adaptation during this mission suggesting that there is a necessity to select the most adaptable crews to maintain high level of performance during winterovering, as well as to prepare the return to the continent. Taken together, these results contribute to a better understanding of adaptation in extremes for future launches into dark space.

Figure 21
Graphical abstract ISHOW

Keywords

Adaptation, Antarctica, Health, Neurosciences, Selection, Third-quarter phenomenon

1. Introduction

« Dreams are not what you have when you sleep. The true dreams are the ones that don't let you sleep », Dr Abdul Kalam (2021).

This is the dream of discovering these white expanses as far as the eye can see that motivated the crew to answer the call of Ernest Shackleton published in the Times in 1913. The 28 most optimistic and motivated individuals were selected for the Endurance odyssey. Their ship caught by the ice pack; they began the most avant-garde expedition in polar history. Even today, it is still difficult to spend a winter on a polar station, despite developments and improvements in equipment. Antarctica is part of the grouping of isolated and confined environments (ICE) as well as extreme and unusual environment (EUE), which makes it a harsh place to live, with danger for the human organism [1,2]. Polar stations are isolated from the rest of the world, crews are confined in small spaces, and unusual with life-support concerns, as well as a limited access to the outer environment, due to the extreme temperatures. The environmental characteristics are unique (e.g., cold, dry, light/dark cycles, sensory deprivation, impossibility to escape). However, the inherent characteristics are even more complex to manage, either physically (e.g., sensory monotony, isolation, impossibility to escape during the winter months, possibility of sudden disaster, physical discomfort, lack of privacy), or psychologically (e.g., cultural differences, empty time, interpersonal issues, distance from loved ones, personal crises). Therefore, living in the white lands of Antarctica presents many challenges.

Changes on body's responses occur during a long stay in extreme environments [3–7]. Data from polar research suggest that overwintering induces a symptomatology including psychosomatic (e.g., fatigue, weight, pains, headaches, digestive complaints), psychological (e.g., depression, anxiety, sleep disturbances, loneliness, fatigue, negative affect, irritability), psychosocial (e.g., tensions, interpersonal conflicts) symptoms, although a salutogenic response has been demonstrated (e.g., friendship, personal achievement, resiliency, coping, sense of humanity, courage, improved health, personal growth) [4, 8–10]. This symptomatology is frequent and tended to follow a non-linear pattern during the mission [11–15], leading to different syndromes. Therefore, patterns due to environmental and psychosocial stressors were highlighted in polar regions [4, 16–21] despite their apparition or frequency were not systematic [19, 22–25]. These include the winter-over syndrome (i.e., sleep disturbance, depression, hostility, negative affect, irritability, distraction, and impaired cognition during the winter period), the third quarter phenomenon (i.e., increase of the symptomology after the midpoint of the mission, with a reduction toward the end), polar T3 syndrome (i.e., variations in thyrotropin-stimulating hormone concentrations with impact on performance and mood), subsyndromal seasonal affective disorder (i.e., depressed mood, lethargy, somatic complaints, appetite, fatigue, decreased performance linked to photoperiodicity), and more recently polar wintering (i.e., psychological hibernation including a decrease as the winter begin and a reconstruction of resources in the second half of the mission). Palinkas and Suedfeld [4] clarified that signs of maladaptation may coexist with salutogenic effects. The literature has highlighted that a positive experience may emerge from ICE/EUE environments [4, 7, 20, 23]. These effects have significant impacts on overwintering and may affect crews after returning to the continent. Overall, adaptation may occur over three stages of perceived reaction in relation to the mission: the initial anxiety stage (i.e., beginning of the mission), a stage of increase depression and boredom (i.e., as the mission progress), and a stage of anticipation including euphoria/aggressiveness (i.e., last period of the mission) [26, 27]. Palinkas and Houseal [28] have proposed that these stages are similar to the Selye's general adaptation syndrome. Nevertheless, it is important to keep in mind that people may not react in the same way of polar regions. Therefore, human adaptation in polar regions seems motivated by a complex intersection of several factors: seasonal, situational, social, and salutogenic [29].

Under stress constraint, an individual will implement mechanisms to cope with the environment and thus maintain an optimal health and operational capacities during the mission. One of the most used mechanisms is the coping framework, considering problem-focused and emotion-oriented strategies [30–32]. Both are considered important to overcome decreased motivation and stressful situations [33]. Nevertheless, the literature on extreme environments refers to many different types of psychological adaptation (e.g., coping strategies, defense mechanisms, emotional regulation, personality, resilience, social support, planification) [3]. Furthermore, coping abilities are not linear and tend to evolve over the course of the mission. Thus, they are dependent on crews, mission, and environmental characteristics. Moreover, interactions with the environment influence the way crews act on it and cope with demands [34]. The available strategies to cope with stressful situation and their use according to the encountered stressful situation has been considered in terms of flexibility in coping, defined as the ability to adapt one's coping strategies in relation to the nature of stressful situations [35]. Flexibility in coping comprises three categories: (a) coping repertoire; (b) coping variability; and (c) coping fitness. Individuals high in coping flexibility are characterized by cognitive astuteness in making distinctions in an array of stressful events [36, 37].

Furthermore, prolonged period of sensory deprivation and monotony may have an impact on body sensory functioning including exteroception and interoception. Both interoceptive and exteroceptive abilities through top-down and bottom-up processes participate in the construction of body awareness, and thus *body matrix* [38]. Impaired visual function has been found in some Antarctica stations, due to the high altitude [1, 20, 39–41]. Nevertheless, Stahl and collaborators [42] did not underline pathological evolutions in ophthalmology of overwinterers (i.e., visual acuity, contrast sensitivity, color vision, auto-refraction, subjective refraction, retinal examination, retinal autofluoresence and retinal thickness, or intraocular pressure). A loss of appetite has also been reported in some studies [4, 43] while in others an increase of appetite has been demonstrated [44–46].

Interoception has been less studied. Defined as the perception of the body's internal signals, interoception has been shown to play a crucial role in the regulation of physiological processes and linked to adaptive coping strategies [47, 48]. This ability participates in the understanding of these interactions and allows to maintain a state of balance (i.e., *homeostasis*). Furthermore, greater heart rate variability (HRV) and interoception are associated with better adaptation in terms of emotions regulation [49]. In line, studies in ICE/EUE have shown that different cardiac biosignal profiles, based on parasympathetic activity and cardiac flexibility, measured by HRV, lead to different adaptation among a patrol on board a nuclear submarine [50, 51]. Authors showed that the differences in terms of interoception and exteroception have an impact on the health of submariners according to the level of parasympathetic baseline level. Thus, HRV participates in body's adaptive response to external environmental constraint highlighting the role of the mind-body connection. Mind-body connection creates opportunities for embodied, embedded (relation with the environment), and extended (i.e., relational experience) [52]. The mind-body connection impacts the multi-sensory representation of their lived experience [53]. As defined by Siegel (p.52) [54], « The human mind is a relational and embodied process that regulates the flow of energy and information ». Mindfulness is a mind-body framework often used as an umbrella term to characterize many functioning characteristics that support adaptation [55]. Nevertheless, mindfulness disposition (MD), characterized by an intentional awareness and non-judgmentally acceptance of pre-moment experiences, refers to body awareness [56, 57] and interoception [55], and it has been related to flow (i.e., feeling of being entirely absorbed) [58]. MD has been associated with improved resilience, flexibility, emotional regulation, and attention in stressful situations [59–62]. A recent study by Lefranc et al. [50] explored the associations between MD, interoception and exteroception. They found that high MD is associated with better interoceptive abilities, positive emotions, and subjective extra-sensor acuity. MD appears to protect against the negative effects of long-term containment in a professional environment, such as a submarine patrol [63]. MD and HRV have been proposed as an indicators of an organism's flexibility, promoting the ability to constantly adapt to changing internal and external environments. Although few studies examine their relationship, there is an increase in MD associated with an improvement in the Autonomic Nervous System (ANS) flexibility measured using HRV self-similarity indicators [64]. These HRV changes have been associated with an increase in the ability to maintain ANS function homeostasis [64].

Furthermore, professionals assigned to ICE and EUE missions, such as polar wintering, are highly selected based on general health mainly based on somatic health and psychological functioning. Goldberg's General Health Questionnaire (GHQ) [65] aims to assess the prevalence of psychological distress by targeting the least differentiated level of mental illness, in other words, the « lowest common denominator » shared by all psychiatric diagnoses. The purpose of this instrument is to discover features that distinguish psychiatric patients from individuals who consider themselves to be healthy, and the questionnaire particularly targets the grey area between psychological sickness and health [66]. Based on the original 60-item version, several versions of GHQ have been constructed to better assess the inability to pursue daily activities and the appearance of new phenomena of a distressing nature within the last few weeks [66]. The purpose of the GHQ was to detect individuals at risk to develop non-psychotic mental health issues among four factors (i.e., depression, anxiety, somatic symptoms, and social dysfunction). The GHQ-12, later developed by Goldberg and Hillier [65], is based on an exploratory factor analysis of the original GHQ-60 and has been translated in more than 38 languages [67]. Mostly used because of its ease of utilization, this version tends to have an efficient specificity, reliability, sensitivity [68–70], and is suitable for studying occupational health [71]. The dimensions of psychological health have been suggested to be universal across cultures [65], and the stability of the factor structures has mostly been confirmed across different cultures and samples [e.g., 69, 72–74]. Although GHQ-12 scores indicate higher levels of distress, a score of 11 or 12 has been proposed as neurotypical whereas scores above 15 have been associated to psychological distress, and above 20 to severe psychological distress [66]. Two types of scores are used in the literature: the bimodal scale (0-0-1-1) and a four Likert scoring scale (0-1-2-3). The Likert scales was preferred to study the levels of psychiatric impairment among a population [75]. During the golden age of scientific studies in Antarctica, authors used the GHQ-12 over the course of a year to study the psychological profiles of winterers at the British Rothera station, and to assess the relevance of using the GHQ in ICE. Their results revealed greater psychological distress during the winter months than in the control group (i.e., stayed in the continent), although this did not persist, with scores remaining relatively stable over the year. Nevertheless, the three winterers who had the highest GHQ scores quitted earlier than planned. Authors added that the GHQ could be a tool for detecting individuals at risk of psychological distress. Therefore, they highlighted the added value of this scale for measuring mental health in Antarctica [76]. More recently, Khandelwal and collaborators [77] studied psychological adaptation at Maitri, an Indian polar station in Antarctica. Results on the 28-items GHQ over the year revealed a significant increase of somatic symptoms, and social dysfunction subscales during the midwinter, followed by a decrease. Anxiety and depression subscales were at the highest during the winter peak.

Thus, in light of these considerations, it may be complex to identify the adaptation mechanisms involved during a winter-over campaign in Antarctuca, especially since there is substantial inter-individual variability [3]. However, better understanding these mechanisms is critical to mission planning, as well as to the prevention and promotion of factors related to successful psychological, social, physiological, and sensory adjustments. The main interest of conducting studies in Antarctica is twofold: on the one hand, to explore the impact of environmental constraint on body's *homeostasis*; and on the other hand, by providing a natural laboratory environment, to study human adaptation in all its components using this natural laboratory. Although several studies have focused on adaptation in ICE/EUE, there are still some missing pieces to understand its mechanisms. This is a real challenge for the ambition of Long-Duration Space Flights (LDSE), for which Antarctica is largely considered as the most suitable analog for Mars [78]. Thus, the main objective of this study is to investigate the impact of a one year stay in Antarctica on psychological, physiological, and sensory responses. This objective was evaluated by considering, among others, the scores at the GHQ-12. Our hypothesis is that subjects with very low at the GHQ-12 at the beginning of the mission will be less impacted by the polar mission. The second exploratory aim is to evaluate the 48-hours short time recovery from this polar mission.

2. Materials & Methods

2.1. Design

The present study (ID-RCB: 2017-A01329-44) was approved by the Committee for the Protection of Individuals (CPP Sud-Est VI, Clermont-Ferrand, France) and was conducted according to the standards of the Declaration of Helsinki. After comprehensive verbal and written presentations, all participants gave their written consent to participate.

2.2. Participants

17 participants (two women and 15 men) were recruited for this study among the crewmembers selected by the French Polar Institute Paul-Émile Victor to participate in the 2021-2022 winter-over campaign at the Dumont d'Urville station, after a medical and psychological screening. Demographics are given as mean ± standard deviation. Mean age was 31.73 ± 10.56 years (ranging from 19 to 55). Among the two women, one (50.00%) was using contraception (i.e., a copper intrauterine device). Only two of the participants were smokers (11.76%) and one was taking 10 mg RAMIPRIL for the treatment of hypertension. Average height was 174.95 ± 6.36 centimeters, and weight 73.82 ± 10.81 kg. 13 participants were single (76.47%), four were in couple (23.52%), among which two (11.76%) had children. Three (17.64%) have already had experience

in the Southern and Antarctic Lands. Upon return, 5 (29.41%) reported that they encountered major stressful events during their wintering.

Table 1 reports sociodemographic characteristics.

Table 1

Socio-demographic characteristics of participants

Measurements	Data*
N	17
Mage	31.73 ± 10.56
Mheight	174.95 ± 6.36
Mweight	73.82 ± 10.81
Gender (women/men)	11.76%/88.23%
Single	76.47%
In couple/with children	23.52%/11.76%
Contraception	50.00%
Major stressful events during wintering	29.41%
Previous experience in Southern and Antarctic Lands	17.64%

*Mean and standard deviation are reported when relevant. Other figures show the ratio of the number of subjects.

2.3. Data collection

2.3.1. Subjective measurements

Sociodemography. A 20-item sociodemographic questionnaire was developed to collect general information on the participant's family situation, medical history, current health status, hobbies, familiarity with extreme environments.

Health. The GHQ evaluates the psychological and psychotic disorders in general population (12 items) [79]. The Coping Flexibility Scale (CFS) assesses coping flexibility defined as the ability to interrupt an ineffective coping strategy (i.e., evaluative coping) and to generate/implement an alternative coping strategy (i.e., adaptive coping) (10 items) [80]. The Leeds Sleep Evaluation questionnaire (LEEDS) evaluates perceived sleep changes, as a function of four sub-factors: sleep onset, sleep quality, sleep arousal, and performance (10 items) [81]. Four additional Visual Analogue

Scales (VAS) were added from the Buguet sleep questionnaire to evaluate the individual's overall status after sleep: desire to work, physical shape; morale; and mood [82]. This four VAS were considered in terms of energy's perception. Physical activity was assessed by a homemade monthly questionnaire evaluating their practice (i.e., type of activity, intensity, length).

Psychology. The Freiburg Mindfulness Inventory (FMI) evaluates mindfulness disposition (14 items) [83]. The scale is divided into two sub-factors that measure presence and acceptation without judgment. Multidimensional Assessment of Interoceptive Awareness (MAIA) evaluates interoceptive awareness (32 items) [84]. The scale is divided into eight sub-factors that measure awareness of uncomfortable, comfortable, and neutral body sensations, the response to sensations of pain and discomfort, the ability to regulate attention to body sensations, and awareness of mind-body integration (i.e., noticing, not distracting, not worrying, attention regulation, emotional awareness, self-regulation, body listening, trusting). The Scale of Positive and Negative Experience (SPANE) assesses subjective feelings of positive and negative affect, based on how frequently they were felt over the previous four weeks (12 items) [85]. The scale is divided into two-subfactors that measure positive and negative affects. The Activation-Deactivation Adjective Checklist (ADAC) evaluates the level of awareness and emotional disposition (28 items) [86]. The scale is divided into two sub-factors: Energetic Arousal (EA, from energy to tiredness) and Tense Arousal (TA, from tension to calmness). EA is further divided into two subscales: general activation and deactivation; and TA is subdivided into general tenseness and calmness. The Perceived Stress Scale (PSS) assesses the subjective stress level (14 items) [87]. The flow experience was assessed using the Educational Flow Questionnaire 2 (EduFlow), which measures flow (12 items) [88]. The scale is divided into four dimensions: cognitive control; immersion and time transformation; loss of self-consciousness; and autotelic experience. Cognitive absorption (i.e., a summary of the first three dimensions) was added as a fourth scale. The Standard Model of Military Group Cohesion (SMMGC) evaluates the social cohesion in military group [89].

Extrasensors. The Personal Hierarchical Sensory (PHS) homemade questionnaire assesses subjective perceptions of vision, sound, touch, olfaction, taste, and equilibrium (1 item). The Sensory Acuity (SA) homemade questionnaire measures subjective exteroceptive acuity for each of the exterosensors: vision, sound, touch, olfaction, taste, and equilibrium (6 items). The Appetite (A) homemade questionnaire evaluates appetite in each domain: level of appetite, satiety, taste of food, hunger at the beginning of meals, hunger outside meals, and number of meals per day (6 items).

2.3.2. Exteroceptive measurements

Olfaction. The European Test of Olfactory Capabilities (ETOC) assesses olfactory sensitivity. Individuals are asked to select a bottle (there are 16 sets of four bottles) that contains an odor versus no odor (a discrimination task) and state the nature of this odor (an identification task). In our experiment, participants were also asked to evaluate the hedonic value of the detected odor.

Audition. The Pure Tone Testing (PTT) is commonly used to test hearing sensitivity in patients, using the Electonica Auditest CE system that enables air conduction measurements. In subjects with normal hearing, it is evaluated using pulsed, ascending tones at frequencies of 125Hz, 500 Hz, 1000 Hz, 2000 Hz, 4000 Hz, 6000 Hz and 8000 Hz, until the individual reports hearing the lowest loudness sound. The instructions that are given to subjects are determinant in the type and quality of the response. In our study, volunteers were placed in the same quiet room and told: « You will hear sounds at different frequencies. Please raise your hand when you hear a sound. The aim of the test is to identify your hearing sensitivity, and not to distinguish if the sound is loud or weak ». Each stimulus was presented for approximately 2 s, with an interval of approximately 1 s between each presentation, until the subject reported discomfort.

Vision. The Parinaud scale (the French equivalent to the Jaeger chart) measures the natural accommodation distance (from the tip of the nose to the reading surface, measured with a tape measure) at which the subject holds a text to read it comfortably. Paragraphs of text are written in decreasing font size. The recommended reading distance to test visual acuity is 33 cm, with a tolerance ranging from 30 to 35 cm. Luminance was controlled with a luxmeter to ensure that the lighting environment was the same for all subjects.

Taste. The Burghart Taste Strips measures the taste abilities. The kit is composed of 16 containers with four concentrations of sweet, salt, sour and bitter, as well as three containers that contained blank strips. The subject is asked to insert a strip on the tip of the tongue and to indicate the identified taste among sweet, salt, sour, bitter, and neutral. Thus, the test evaluates both the taste detection threshold, and the identification of flavors.

2.3.3. HRV

Electrocardiogram (ECG) signal was recorded for a ten-minute period to extract heartbeat interval data (RR), with subjects in a sitting position, using a Kino® wearable cardiac monitoring device (Heartkinetics, Belgium), at a sampling frequency of 500 Hz. Data were stored on a SD card and analyzed offline.

The HRV analysis followed guidelines reported in [90, 91], which take into account potential circadian variation, and used the *PyHRV* python library [92]. The following data were recorded: weight; height; waist-to-hip ratio; smoking habits; most recent alcohol intake (>24h); most recent caffeinated (coffee/ tea) intake (>1h); most recent meal (>2h); most recent physical activity (>12h); and quality of sleep on the day of the experiment and the preceding day.

Raw ECG data were filtered using a band-pass filter (0.5–80 Hz). The order of the filter was set at 54 (0.3 times the sampling frequency). R peaks were automatically detected using the *BioSPPy* Python library [93]. A Hamilton segmentation was performed on the filtered signal, followed by R-peak correction with tolerance set to 0.05. R-waves were manually examined to ensure correct detection. If an ECG sequence was overly noisy when visualizing the superposition of all QRS complex, the time interval was manually removed to improve data quality. RR intervals were automatically detected with the *hrvanalysis* module using linear interpolation, and manually corrected for artifacts and ectopic beats.

Time domain analysis. Time domain HRV metrics included mean RR (the mean interbeat interval), SDNN (Standard Deviation of the Normal-to-Normal RR interval), RMSSD (Root Mean Square of Successive Differences between adjacent RR intervals), and pNN50 (percentage of adjacent NN intervals that differ from each other by more than 50 ms).

Frequency domain analysis. Frequency domain HRV metrics complemented time domain metrics and included oscillatory components of heart rate dynamics. Spectral density was estimated using Welch's method: low frequencies (LF, sympathetic and parasympathetic activity) in the range 0.04–0.15 Hz, and high frequencies (HF, parasympathetic activity) in the range 0.15–0.4 Hz, LF/HF ratio in absolute powers (ms^2).

Nonlinear analysis. Nonlinear HRV metrics reflect dynamic and chaotic internal states that other metrics cannot reflect. The most representative metrics were used: SD1 (i.e., standard deviation of instantaneous interbeat interval variability) and SD2 (i.e., standard deviation of continuous, long-term RR variability) extracted from the poincaré plot (i.e., graphical representation of the correlation between successive interbeat intervals), α1 (i.e., detrended fluctuation analysis self-similarity parameter that represent short-term fluctuations), α2 (i.e., detrended fluctuation analysis self-similarity parameter that represent long-term fluctuations), sample entropy (i.e., regularity and complexity of time series).

2.4. Experimental design

The experiment was conducted during the 2021-2022 overwintering season at the Dumont d'Urville station (DDU). DDU is a French polar station located on the coast of Adelie land, in the East of Antarctica facing Tasmania (66°39′S – 140°0′E). The climate was mild with an annual temperature of -10.4°C, and records of -31.1°C in June and 5.2°C in December. They were 369.1 hours of sunshine in January contrary to 9 hours in June. Due to the climate, DDU is only accessible between October and March of each year using the Astrolabe, an ice-breaker vessel. Thus, the station is isolated from the rest of the World during approximately seven months each year.

Psychological, physiological and exteroceptive responses were evaluated at different time intervals during one year at DDU upon participants' arrival at the station. These measures were performed by the medical doctor of the station during the wintering period.

Psychological baseline assessments were performed the day of the arrival on the station (M0). During the wintering, all measures were performed at month 4, 7, 10 or 12 (M4, M7, M10 or M12). Recovery assessments took place two days upon the return from DDU (D+2) on eight participants (i.e., winterers did not return to the continent on the same rotation). Psychological data were assessed at M0, M4, M7, M10, and D+2. Physiological, and exteroceptive data were assessed at M4, M7, M12, and D+2. No pre-mission baseline was recorded because of the sanitary restrictions due to covid-19 pandemic applied by the French Polar Institute Paul-Émile Victor. Recovery data were only recorded at D+2 as subjects has finished their contract with the French Polar Institute Paul-Émile Victor at that time.

2.5. Statistical methods

Statistics were computed for all outcome measures. Data analyses were performed with JASP (Amsterdam, version 0.16.3), an open-source software package that is used for both classical and Bayesian analyses. Descriptive statistics were expressed as mean ± SD. The Shapiro–Wilk test was used to determine whether data were normally distributed. When the analysis was significant, effect sizes were reported. Psychological adaptability was evaluated using the score at the GHQ, aiming at evaluates non-psychiatric and minor psychotic disorders in the general population. In this sense, we considered the hypothesis that we had different groups based on their score on the GHQ scale. Thus, the median on their GHQ score was used as a threshold to separate the overall population in two groups of profiles: the Hors Norm (HN) profile that have the lowest GHQ score (i.e., very limited or no existence of minor non-psychiatric or psychotic disorders) and the Ordinary (OR) profile that have a standard GHQ score (i.e., standard values for non-psychiatric or minor psychotic disorders within the general population) at baseline.

Psychological, physiological, and exteroceptive responses were evaluated using ANOVA repeated-measures analyses ranging from M0 to M12, and D+2. Holm *post hoc* analyses were performed when the *p*-value was significant. Bayesian analyses were performed, by applying equivalent analyses for ANOVA repeated-measures analyses. The Bayesian Factor (BF) was calculated if no significant effect was detected. A low value provides support for the null hypothesis, and a high value indicates evidence in favor of the alternative hypothesis (i.e., BFs are presented in Supplementary Material and did not include recovery measures). For all analyses, statistical significance was set at $p < .05$. A *p*-value between .05 and .07 was considered as evidence of a trend. Only significant or trend results are presented.

3. Results

Baseline measurements from the day of the arrival on the station (M0) are presented for all participants per groups in Table 2 (Supplementary Material). No differences were found between the two groups based on the GHQ at baseline for psychological, physiological and sensory measurements, apart from subjective stress (p = .023), calmness (p = 035), loss of self-consciousness of flow (p = .059), cognitive absorption of flow (p = .045), and performance after getting-up ($p < .001$). Among the HN and OR profiles, GHQ score ranged from 3 to 14 (8.44 ± 3.32). In consequence, the distinction between the two groups based on the median is established from a score within the norm for the general population (i.e., the median value is 8.00).

Table 2

Health & psychological measures during wintering

	Baseline		Month 4		Month 7		Month 10		*p*-value[*]
	OR	HN	OR	HN	OR	HN	OR	HN	
GHQ									
H[c]	6.250 ± 1.961	11.571 ± 2.070	6.700 ± 3.561	12.143 ± 7.537	8.900 ± 3.178	10.429 ± 5.255	8.200 ± 2.898	11.143 ± 2.854	< .001
FMI									
A[c]	25.400 ± 2.591	23.286 ± 3.147	25.100 ± 3.281	20.429 ± 4.117	24.256 ± 3.217	22.286 ± 2.928	23.400 ± 1.955	21.143 ± 3.436	.015
MAIA									
SR[c]	3.107 ± .643	3.600 ± .899	2.786 ± .466	3.725 ± .661	3.107 ± .762	3.725 ± 1.244	3.143 ± 1.162	3.850 ± .679	.071
SPANE									
N[c]	1.967 ± .874	2.381 ± 1.145	1.467 ± .429	2.405 ± .526	1.650 ± .461	2.073 ± .470	1.700 ± .375	2.405 ± .607	.003
AD-ACL									
Ti[a]	2.100 ± 1.197	3.527 ± 2.242	1.500 ± 1.716	6.000 ± 3.830	3.000 ± 2.981	4.857 ± 2.734	3.400 ± 1.897	6.429 ± 3.867	.057
Te[c]	.900 ± 1.101	2.661 ± 2.239	.200 ± .422	3.286 ± 3.546	.000 ± .000	2.571 ± 2.820	.463 ± .958	2.857 ± 2.116	< .001
C[c]	11.100 ± 2.132	8.580 ± 2.306	10.200 ± 2.251	7.286 ± 3.039	10.800 ± 1.317	8.429 ± 2.760	9.100 ± 2.331	7.429 ± 2.699	.011
LEEDS									
Tg[a]	7.600 ± 2.119	2.045 ± 2.379	6.700 ± 2.710	.857 ± 4.947	3.500 ± 5.563	3.714 ± 2.690	4.000 ± 4.667	.286 ± 4.680	.011
P[b,c]	-.600 ± 1.713	.402 ± 1.148	.800 ± 1.476	1.143 ± 1.464	.500 ± 1.434	2.000 ± 2.708	-.500 ± 1.581	-.571 ± 1.988	.052
BUGUET									
D[a]	.000 ± .000	.455 ± .773	.600 ± 1.075	1.857 ± 1.952	1.100 ± 1.197	1.143 ± 1.773	1.000 ± 1.491	2.000 ± 1.291	.009
Mf[c]	4.900 ± .994	4.536 ± 1.262	5.200 ± .789	3.857 ± 1.574	4.900 ± 1.101	4.429 ± 1.512	5.000 ± 1.054	3.571 ± 1.718	.025
M[a,c]	5.500 ± .707	5.196 ± .692	5.200 ± .919	4.429 ± .976	5.100 ± .994	4.286 ± 1.254	5.100 ± 1.101	3.571 ± 1.618	.004

PSS									
S[a,c]	11.700 ± 4.832	18.196 ± 5.714	9.400 ± 4.477	20.571 ± 9.199	5.600 ± 4.551	9.571 ± 5.028	11.900 ± 5.547	21.857 ± 6.203	< .001
SIEBOLD									
TC[a]	15.287 ± 2.671	14.267 ± 3.143	17.000 ± 2.404	17.143 ± 3.185	16.300 ± 2.869	16.857 ± 3.288	15.188 ± 2.430	13.714 ± 4.645	.015
PHS									
V[a]	8.000 ± 2.309	8.304 ± 1.250	1.400 ± .699	1.857 ± 1.464	1.100 ± .316	1.571 ± 1.134	1.444 ± .956	1.429 ± 1.134	< .001
SA									
V[a]	9.000 ± 1.054	9.000 ± .816	8.300 ± 1.059	8.714 ± 1.254	8.600 ± 1.776	7.857 ± 2.410	8.500 ± 1.581	7.571 ± 2.440	.059
H[a]	8.300 ± 1.252	8.482 ± .502	7.700 ± 1.703	8.000 ± .816	7.200 ± 1.989	7.857 ± 1.952	7.000 ± 1.886	6.857 ± 2.116	.010
Ta[a]	7.100 ± 2.378	8.375 ± 1.013	6.300 ± 2.263	7.571 ± 1.718	6.000 ± 1.826	6.857 ± 1.676	5.900 ± 2.183	6.286 ± 1.380	.026
A									
LA	3.991 ± .578	3.900 ± .876	4.143 ± .690	3.700 ± .675	4.143 ± .690	3.700 ± .675	3.286 ± .488	3.000 ± 1.247	< .001
TF	4.161 ± .373	4.100 ± .373	4.714 ± .488	3.800 ± .632	4.714 ± .488	3.800 ± .632	3.571 ± 1.272	3.200 ± .789	< .001
MD	3.835 ± .687	3.850 ± .747	4.000 ± .816	3.600 ± .699	4.000 ± .816	3.600 ± .699	3.286 ± .488	3.300 ± .675	.001

Note. OR = standard values for non-psychiatric or minor psychotic disorders within the general population; HN = very limited or no existence of minor non-psychiatric or psychotic disorders; H = health; A = acceptation; SR = self-regulation; N = negative emotions; Ti = tiredness; Te = tension; C = calmness; Tg = time to get up; P = performance after wake-up; D = desire to work; Mf = moral feeling; M = mood; S = subjective stress; TC = team cohesion towards leader; V = vision; H = hearing; Ta = taste; LA = level of appetite; TF = taste of food; MD = meals per day.

[*] *p*-value used in the analysis of effects. Means and standard deviations are shown for each variable. All variables were recorded at four times, appart from proprioception where baseline and recovery were collected. Only significant interactions were reported ($p < .05$).

[a] Significant time effect.

[b] Significant time*group effect.

[c] Significant group effect.

3.1. Health and psychological changes during the mission according to profiles

Mindfulness disposition. There is a significant effect of group on acceptation [F (1,15) = 7.599, p = .015, η^2 = .166]. Participants with a OR profile would have a lower acceptation than those with a HN profile.

Interoception. A trend to a group effect was identified for self-regulation [F (1,15) = 3.742, p = .071, η^2 = .146]. Participants with a OR profile tend to have less ability to regulate their psychological distress by paying attention to body sensations than those with a HN profile.

Affects. There is a significant group effect [F (1,15) = 19.484, p < .001, η^2 = .277] and a trend to a time effect [F (3,45) = 2.648, p = .060, η^2 = .074] on negative affects. Participants with a OR profile have higher negative affects than those with a HN profile. *Post hoc* analyses found that winterers tend to have fewer negative affects at month 7 compared to baseline (p = .072).

Thymia. There are significant time effects for tiredness [F (3,45) = 2.695, p = .057, η^2 = .063], and group effects for tension [F (1,15) = 40.147, p < .001, η^2 = .324] and calmness [F (1,15) = 8.426, p = .011, η^2 = .324]. *Post hoc* analyses found that winterers had an increase in tiredness at month 10 compared to baseline (p = .041). Moreover, those with a OR profile have higher tension, and lower calmness than those with a HN profile.

Sleep quality. There are significant effects of time [F (3,45) = 4.175, p = .011, η^2 = .159] on time to get up, as well as a time*group [F (3,45) = 2.775, p = .052, η^2 = .045], and group [F (1,15) = 8.222, p = .012, η^2 = .173] effects on performance after wake-up. *Post hoc* analyses show that winterers get up earlier at month 10 (p = .024) compared to month 7. Those with a OR profile rate worse performance after wake-up at month 4 (p = .030) and month 10 (p = .013) compared to those with a HN profile at baseline, and at month 10 compared to month 4 (p = .047). Moreover, those with a OR profile rate worse performance after wake-up than those with a HN profile.

Perceptions of energy. There are significant time effects for desire to work [F (3,45) = 4.381, p = .009, η^2 = .120], and mood [F (3,45) = 5.071, p = .004, η^2 = .097], as well as significant group effects for moral feeling [F (1,15) = 6.231, p = .025, η^2 = .121], and mood [F (1,15) = 4.519, p = .051, η^2 = .134]. *Post hoc* analyses found that winterers had more desire to work at month 10 compared to month 4 (p = .008), and a decrease in mood at month 10 compared to baseline (p = .002). Moreover, those with a OR profile have a worse moral feeling and mood than those with a HN profile.

Subjective stress. There is a significant time [F (3,45) = 9.791, p < .001, η^2= .212] and group effect [F (1,15) = 23.297, p < .001, η^2= .261] on stress perception. *Post hoc* analyses reveal that winterers perceived less stress at month 7 compared to baseline (p = .001), month 4 (p = .001) and month 10 (p < .001). Also, those with a OR profile perceived higher subjective stress than those with a HN profile.

Team cohesion. There is a significant effect of time regarding interactions with the leader [F (3,45) = 3.877, p = .015, η^2= .005]. *Post hoc* analyses reveal a decrease in leader/subordinate relationships at month 10 compared to month 4 (p = .044).

Sensory evaluation. There is a significant time effect on preference for vision [F (3,45) = 121.390, p < .001, η^2 = .064]. *Post hoc* analyses reveal that winterers decreased their preference for vision towards other senses at month 4 (p < .001), month 7 (p < .001), and month 10 (p < .001) compared to baseline.

Subjective exteroceptive acuity. There are significant effects of time on vision [F (3,45) = 2.670, p = .059, η^2 = .051], hearing [F (3,45) = 4.266, p = .010, η^2 = .101], and taste [F (3,45) = 3.385, p = .026, η^2 = .096]. *Post hoc* analyses showed that winterers reduced ability to trust their hearing (p = .010), taste (p = .027) and a trend for visual (p = .065) environment at month 10 compared to baseline.

Appetite. There are significant effects of time on level of appetite [F (3,45) = 8.331, p < .001, η^2 = .160], taste of food [F (3,45) = 8.364, p < .001, η^2 = .200], and number of meals per day [F (3,45) = 1.384, p = .001, η^2 = .097]; as well as a group effect on taste of food [F (1,15) = 6.828, p = .020, η^2 = .122]. *Post hoc* analyses showed that at month 10, winterers had a decrease of their level of appetite compared to baseline (p < .001), month 4 (p = .001), and month 7 (p = .001), in their taste in food compared to baseline (p = .003), month 4 (p < .001) and month 7 (p < .001); and a decrease in their number of meals per day compared to baseline (p = .003), month 4 (p = .006), and month 7 (p =

.006). Also, those with a OR profile perceived higher taste of food than those with a HN profile.

A summary of these psychological differences during wintering is presented in Table 2. Differences in interoceptive pathways between profiles appears in Figure 1, those associated to thymia in Figure 2 and those associated to others psychological factors in Figure 3.

Figure 1
Interoceptive pathways among profiles during one year in Antartica

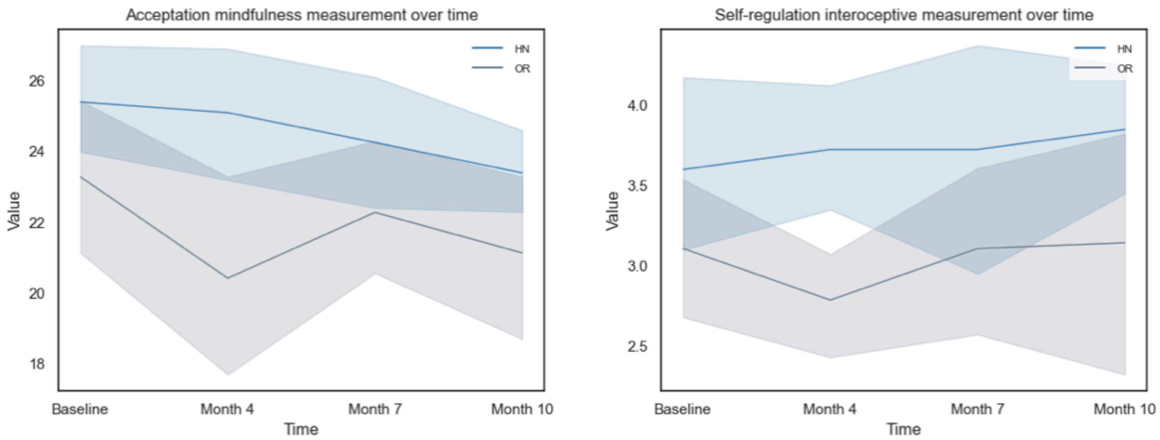


Figure 2
Thymia functioning among profiles during one year in Antarctica

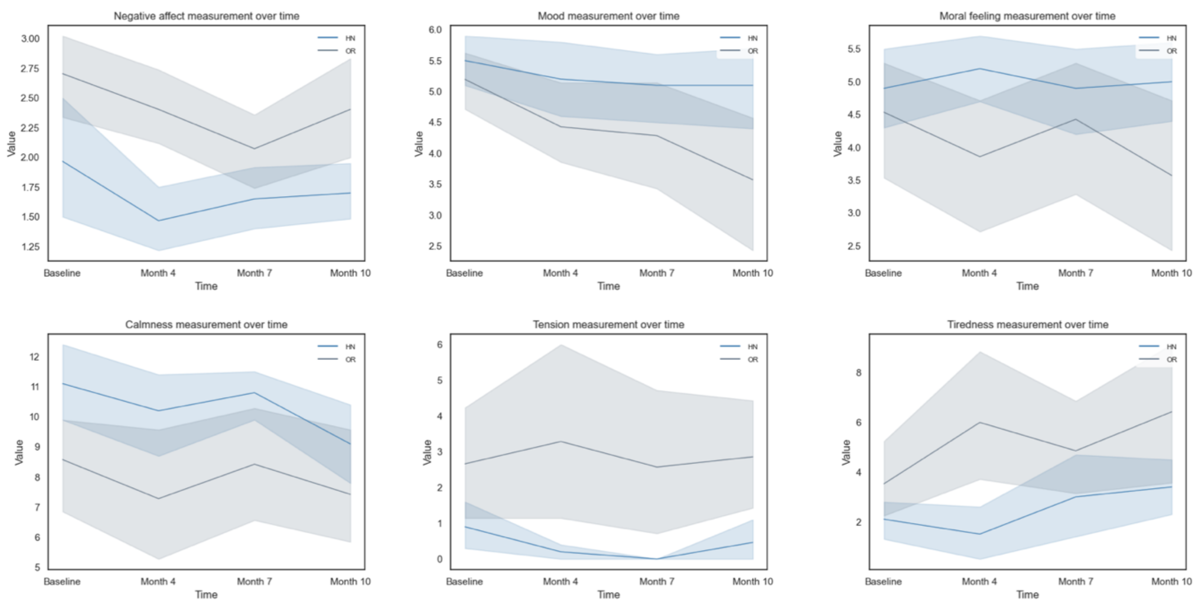
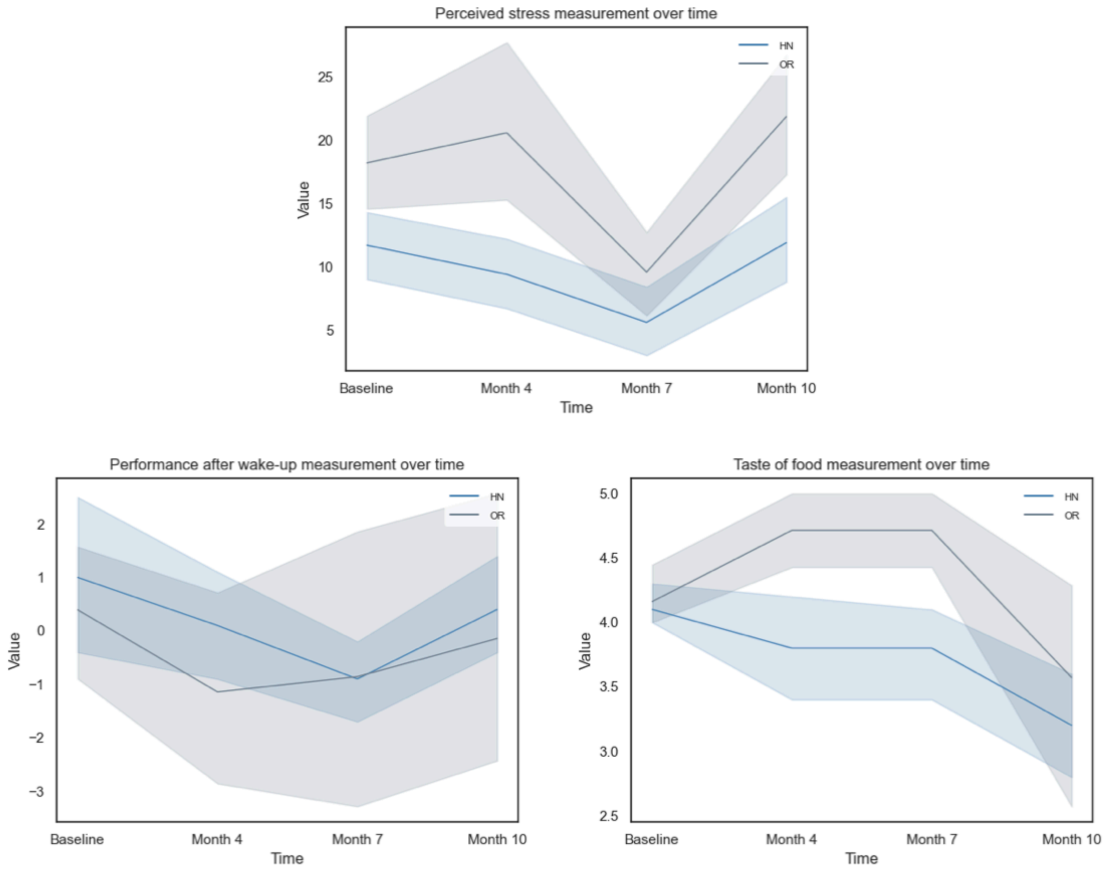


Figure 3
Other psychological factors among profiles during one year in Antarctica



3.2. Physiological and exteroceptive changes during the mission according to profiles

HRV. There is a significant time effect for RR intervals [F (3,30) = 5.316, p = .011, η^2 = .291]. *Post hoc* analyses show that winterers have higher RR intervals at month 7 compared to month 12 (p = .009).

Olfaction. There is a significant group effect for hedonic value [F (1,15) = 12.567, p = .003, η^2 = .350]. Participants with a OR profile have a better hedonic value than those with a HN profile.

PTT. Significant differences were found for both ears. For the right ear, there is a significant time effect at 125 Hz [F (2,30) = 3.806, p = .034, η^2 = .055], at 1000 Hz [F (2,30) = 3.864, p = .032, η^2 = .083], at 4000 Hz [F (2,30) = 5.041, p = .013, η^2 = .083].

At 125 Hz, there are significant group effects for the right [F (1,15) = 7.805, p = .014, η^2 = .292], and the left ear [F (1,15) = 6.047, p = .027, η^2 = .202]. *Post hoc* analyses showed that winterers have a better sensitivity at different frequencies: in 125 Hz frequencies at month 12 compared to month 7 (p = .049), with a trend at month 4 (p = .072); in 4000 Hz at month 12 compared to month 4 (p = .011). Also, they tend to have an increase in sensitivity in 1000 Hz frequencies at month 12 compared to month 4 (p = .066) and month 7 (p = .066). Both at the right and left ears, participants with OR profile have a higher sensitivity at 125 Hz than those with a HN profile.

Vision. There is a significant effect of time for distant focus [F (3,45) = 12.682, $p < .001$, η^2 = .181]. *Post hoc* analyses showed that winterers have a more distant focus distance ($p < .001$) at month 7 compared to month 4.

Taste. There is a significant group effect for taste [F (1,15) = 9.072, p = .009, η^2 = .155]. Participants with OR profile have worse taste abilities than those with a HN profile.

Table 3 presents a summary of these physiological and exteroceptive differences following the wintering. Figure 4 represents exteroceptive differences between profile.

Table 3

Exteroceptive measures during wintering

	Month 4		Month 7		Month 10		*p*-value*
	OR	HN	OR	HN	OR	HN	
HRV							
NNI[a]	-4.000 ± 5.676	7.857 ± 15.774	-2.500 ± 7.546	12.143 ± 17.043	-5.500 ± 4.378	10.000 ± 16.073	.011
PTT							
125 Hz LE[a,c]	-4.000 ± 5.676	7.857 ± 15.774	-2.500 ± 7.546	12.143 ± 17.043	-5.500 ± 4.378	10.000 ± 16.073	.034
1000 Hz LE[a]	2.500 ± 9.789	6.429 ± 6.268	1.500 ± 11.559	7.143 ± 6.362	1.500 ± 11.559	2.857 ± 4.880	.032
4000 Hz LE[a]	3.000 ± 11.595	.000 ± 7.638	.000 ± 12.019	-4.286 ± 7.319	.500 ± 14.034	-2.857 ± 9.063	.013
125 Hz RE[c]	-2.500 ± 5.893	6.429 ± 15.999	-4.500 ± 7.619	10.000 ± 13.540	-6.000 ± 6.583	.000 ± 7.638	.027
PARINAUD							
Df[a]	85.900 ± 9.219	80.429 ± 21.298	98.000 ± 11.441	100.429 ± 14.797	87.300 ± 14.024	94.000 ± 16.042	< .001
Taste							
T[a]	12.900 ± 1.729	11.000 ± 3.416	13.900 ± 2.998	9.286 ± 4.461	13.100 ± 2.644	11.714 ± 3.546	.009

Note. OR = standard values for non-psychiatric or minor psychotic disorders within the general population; HN = very limited or no existence of minor non-psychiatric or psychotic disorders; NNI = mean of successive RR intervals; Df = distant focus; T = taste; LE = left ear; RE = right ear.

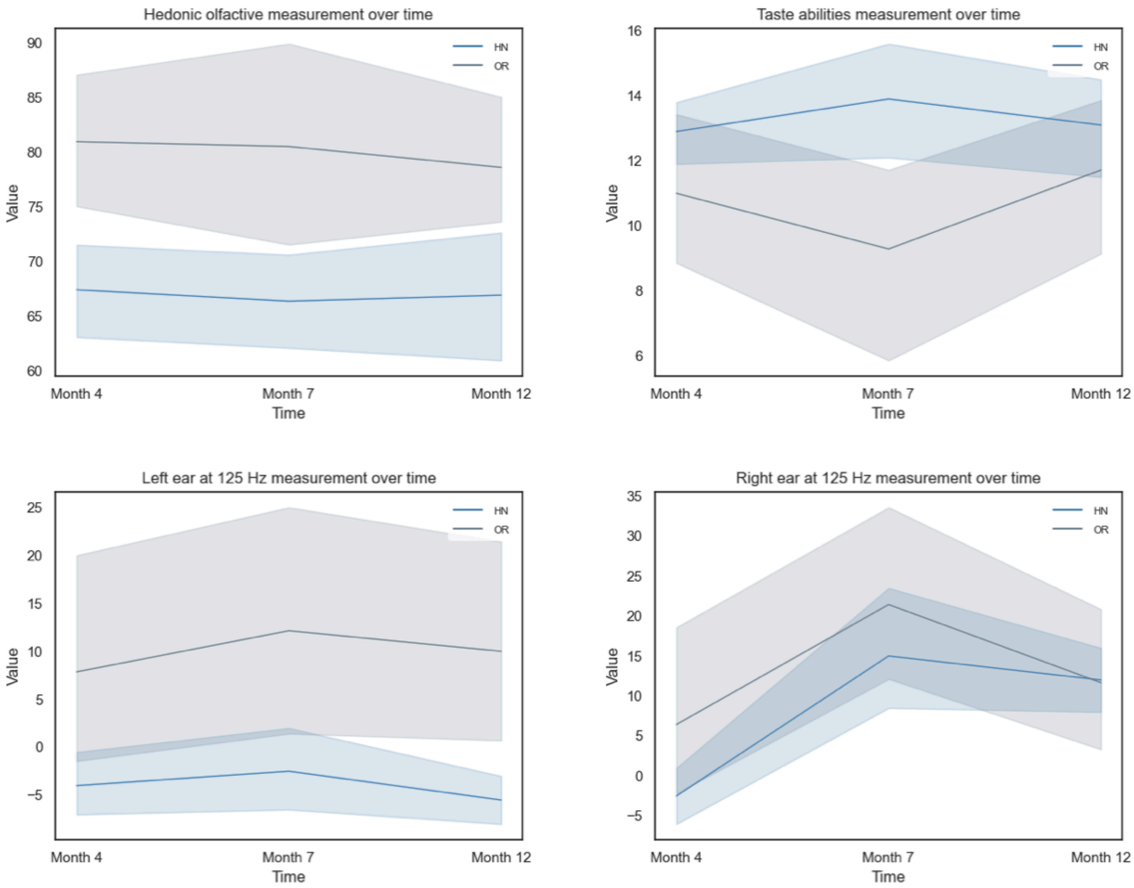
* *p*-value used in the analysis of effects. Means and standard deviations are shown for each variable. All variables were recorded at four times, apart from proprioception where baseline and recovery were collected. Only significant interactions were reported ($p < .05$).

[a] Significant time effect.

[b] Significant time*group effect.

[c] Significant group effect.

Figure 4
Exteroceptive differences among profiles during one year in Antarctica



3.3. Measures at recovery (D+2) according to groups

Interoception. There are significant time effects for noticing [F (4,24) = 3.695, *p* = .018, η^2 = .119], and self-regulation [F (4,24) = 4.084, *p* = .012, η^2 = .090], as well as a trend on attention regulation [F (4,24) = 2.536, *p* = .066, η^2 = .286]. Also, there is a time*group effect on self-regulation [F (4,24) = 2.912, *p* = .043, η^2 = .064]. *Post hoc* analyses showed that at D+2, winterers have a decrease in their awareness of uncomfortable, comfortable, and neutral body sensations compared to baseline (*p* = .012), in their ability to maintain and control attention to body sensations compared to month 7 (*p* = .059), and to regulate psychological distress by paying attention to body sensations compared to month 10 (*p* = .041). Moreover, participants with OR profile have a decrease in their ability to regulate psychological distress by paying attention to body sensations at D+2 compared to month 10 (p = .036).

Perception of energy. There is a significant effect of time for desire to work [F (4,24) = 6.888, p < .001, η^2 = .304], moral feeling [F (4,24) = 6.430, p = .001, η^2 = .412], and mood [F (4,24) = 11.728, p < .001, η^2 = .451]. *Post hoc* analyses showed that at D+2, winterers have an increase in desire to work compared to baseline (p < .001), month 4 (p = .010), month 7 (p = .003), and month 10 (p = .010); an increase in mood compared to baseline (p = .008), month 4 (p < .001), month 7 (p = .001), and month 10 (p < .001); as well as a decrease in moral feeling compared to baseline (p = .004), month 4 (p = .030), month 7 (p = .001), and month 10 (p = .053).

Flow. There are significant time [F (4,24) = 5.385, p = .003, η^2 = .113] and time*group effects [F (4,24) = 3.373, p = .025, η^2 = .071] for loss of self-consciousness. *Post hoc* analyses showed that winterers have a decrease in their ability to be absorbed by an activity at D+2 compared to baseline (p = .022). Moreover, those with a OR profile have a lower loss of self-consciousness at baseline (p = .003), month 4 (p = .015), month 7 (p = .013), and month 10 (p = .027) compared to those with a HN profile at D+2. Also, they have a lower loss of self-consciousness at D+2 compared to those with a OR profile at month 7 (p = .016) and month 10 (p = .004). At D+2, winterers with a OR profile have a worse loss of self-consciousness compared to those with a HN profile (p = .003). The HN profile has a greater loss of self-consciousness at D+2 compared to baseline (p = .009).

Sensory evaluation. There is a significant time effect on vision [F (4,24) = 3.577, p = .020, η^2 = .031]. *Post hoc* analyses reveal that winterers decrease their subjective preference for vision towards other senses at D+2 compared to month 4 (p = .020).

Appetite. There is a significant time effect on taste of food [F (4,24) = 7.264, p < .001, η^2 = .409]. *Post hoc* analyses reveal that winterers have a decrease in subjective taste of food at D+2 compared to month 4 (p = .019).

HRV. There is a significant time effect for RR intervals [F (3,18) = 3.013, p = .057, η^2 = .225]. *Post hoc* analyses show that winterers have lower RR intervals at D+2 compared to month 7 (p = .051).

Olfaction. There is a significant time effect for detection [F (3,18) = 6.687, p = .003, η^2 = .416]. *Post hoc* analyses showed that winterers have a decrease in their ability to detect odors at D+2 compared to month 4 (p = .007), month 7 (p = .007) and month 12 (p = .036).

Vision. There is a significant effect of time for distant focus [F (3,18) = 5.584, p = .007, η^2 = .358]. *Post hoc* analyses showed that winterers have a more distant focus distance at month 7 compared to D+2 (p = .026).

Table 4 reported a summary of the recovery measures performed at D+2.

Table 4

Recovery measures at D+2

	Recovery		*p*-value*
	OR	HN	
MAIA			
N[a]	3.000 ± .433	3.333 ± 1.181	.018
SR[a,b]	2.550 ± 1.095	3.750 ± .661	.012
AR[a]	2.714 ± 1.187	2.762 ± .577	.066
BUGUET			
D[a]	4.333 ± 3.512	6.200 ± 4.382	< .001
Mf[a]	1.333 ± .577	3.000 ± 1.581	.001
M[a]	7.667 ± 2.517	7.600 ± 1.817	< .001
FLOW			
L[a,b]	19.000 ± 3.464	9.400 ± .894	.003
PHS			
V[a]	1.000 ± .000	1.600 ± 1.342	.020
A			
TF[a]	3.600 ± .548	4.000 ± .000	< .001
HRV			
NNI[a]	821.672 ± 28.890	781.179 ± 140.439	.057
ETOC			
V[a]	14.111 ± 1.836	15.333 ± .408	.003
PARINAUD			
Df[a]	77.667 ± 15.567	73.700 ± 14.721	.007

Note. OR = standard values for non-psychiatric or minor psychotic disorders within the general population; HN = very limited or no existence of minor non-psychiatric or psychotic disorders; N = noticing; SR = self-regulation; AR = attention regulation; D = desire to work; Mf = moral feeling; M = mood; L = loss of self-consciousness; V = vision; TF = taste of food; NNI = mean of successive RR intervals; Df = distant focus.

**p*-value used in the analysis of effects. Means and standard deviations are shown for each variable. All variables were recorded at four times, appart from proprioception where baseline and recovery were collected. Only significant interactions were reported ($p < .05$).

[a] Significant time effect.

[b] Significant time*group effect.

4. Discussion

The nature of Antarctica makes it one of the most inhospitable places on Earth, but also one of the most exciting places to live and work. Since the first expeditions to Antarctica, scientific studies have reported how challenging life on board these stations was. For years, research has focused on understanding the psychophysiological and cognitive impact of wintering [3, 4, 23]. Recently, a new dynamic has been instilled since salutogenic effects could also take place. A one-year mission in Antarctica is therefore no longer necessarily pathogenic but, on the contrary, would allow for an improvement in the state of health and a personal evolution specific to each individual [3, 23, 78]. A growing body of literature is exploring the mechanisms underlying adaptation in these unique environments [94–97]. This is especially important because, besides improving the living conditions in the polar regions, it also benefits those of crews in outer space. Even if its environmental and mission conditions are not optimal to be considered as a perfect analogue, its characteristics remain unique and shared (e.g., advanced life support system, crew selection, isolation, and confinement) with those that will be posed by the LDSE [78, 98–101]. Thus, research in Antarctica represents a unique opportunity to reduce health risks before they jeopardize the mission. Therefore, the aims of this study were: (1) to investigate the impact of a one year stay in Antarctica on psychological, physiological, and sensory responses; and (2) to assess recovery from this experience, two days after return to civilization. Each of these objectives considered the level of mental health through the GHQ-28 measured in baseline. Our results highlight that one year of wintering does not represent a serious threat for the health and psychological, physiological, and sensory functioning of the winterers, that winter may experience stable states, indicating adaptability while the last part of the mission seems to constitute a challenge for the crew. Two days after returning to the continent, the winterers show psychophysiological and sensory stress. Moreover, based on the results observed in the OR at baseline, they underline the importance of screening before departure, and a better adaptation for those who have no risk of psychological disorders.

4.1. Sustained experience of winterovers and third-quarter phenomenon

Winterers perceived less subjective stress, tend to have fewer negative affects during the winter peak. These results suggest that the mind-body connection is maintained, with only small changes in mindfulness and interoceptive functioning, mainly for the OR group. We also observed a decreased in appetite (i.e., level of appetite, taste of food, number of meals per day). Furthermore, they have an increase in their RR intervals the last month of the wintering. Therefore, these results reflect that the winter month known to be the harshest of the season induces positive outcomes in winterers. Many studies have shown winter to be a crucial time in ICE/EUE, exhibiting sleep disturbances [47, 102–104], mood changes [7, 28, 46, 47], interpersonal disorders [7, 94, 105–108]. These changes have been referred to under the name 'winter-over syndrome' [43]. Nevertheless, our results are in line with evidence that ICE and EUE do not necessarily induce pathogenic but a normal stable functioning. Contrary to other studies [2, 3, 4, 18, 23, 94], no clear salutogenic consequences were observed with the recorded variables in terms of mindfulness functioning or positive affects. Anthonovsky [110] was the first to introduce that stress could be beneficial and induce positive outcomes on health. Palinkas and Suedfeld [23] highlighted that the severity of the environment is inversely correlated with a negative mood. A recent study [97] highlight that the depressive and anxiety symptoms did not exceed the threshold for mental disorders throughout the year. Palinkas & Suedfeld [4] pointed out that psychological disorders were rare in Antarctica with a decrease in their rate of occurrence. They even noted that staying in Antarctic improves abilities to deal with stress, and thus coping strategies. Levine and Ursin [111] underlined that body's response is motivated by the meaning attached to the experience rather than the environmental stressors alone.

Furthermore, winterers have fewer preference for vision towards other senses during the winter months and a more distant focus distance during the winter spike. The winter spike corresponds to the month with the lowest sunshine rate of the year. On average, it was between -18.2°C and -13.3°C, 0mm of precipitation, and 00 min / 1 kWh/m^2 of sunshine. In comparison, at the beginning of the winter there was an average of between -16.5°C and -10.8°C, 0 mm of precipitation, and 115 h 40 min / 23 kWh/m^2 of sunshine. Therefore, winterers seem to have better distance vision during the winter month, where there is the lowest sunshine rate. This result appears to reflect an adaptation of visual accommodation. A 2013 overwintering study [42] had explored ophthalmological changes before and upon return from an 8-month expedition. No damage to the eye was evident suggesting that visual function remained unchanged after exposure to ICE/EUE.

Nevertheless, there are patterns of temporality for which adaptation is not a linear mechanism. Our results show that from October (M10) onwards, there is a symptomology that highlights that the last quarter of the mission seems to constitute a period of stress. On the psychological level, there are an increase in tiredness, subjective stress, and a decrease in mood; despite an increase in desire to work. Furthermore, they get up earlier. On the social level, there is a decrease in cohesiveness with the leader compared to the beginning of the winter. Nevertheless, although tensions exist [23, 23, 94, 112], conflicts remain relatively low on the wintering year [18]. The leader and the group form the primary group cohesion-based trust and teamwork, and is associated with performance [113]. A study [114] analyzing the cohesion in a US army medical unit found an inverted U pattern in a 6-months mission. Cohesiveness seems to begin low, reached its highest point at mid-deployment and decrease during the third quarter of the deployment. The late decrease appeared to be associated with work relationships issues, boredom, and trust in leaders.

On the sensory level, fewer preference for vision towards other senses, and reduced subjective acuity for hearing, taste, and a trend for vision were found. Furthermore, they have a better sensibility to sound stimuli for the right ear at 125 Hz, 1000 Hz and 4000 Hz compared to the winter months. These findings are consistent with those reported in previous studies in extreme environments [50, 51, 115]. These studies show a decrease in their threshold for auditory discomfort for the right ear at 500 Hz, 1000 Hz, and 2000 Hz in submarine patrols during the third quarter of the mission [50, 51] and at 1000 Hz, 2000 Hz, 4000 Hz and 8000 Hz during a simulation at sea of five days [115]. Therefore, they seem to develop an auditory hypersensitivity to sensory stimuli. Authors have pointed out that the right ear plays an important role in hearing processing [116, 117].

Therefore, our study seems to indicate a third-quarter phenomenon, highlighted by a critical period during the last quarter of the mission, mainly observed at M7 and M10, on the psychological and sensory level [118, 119]. Several authors have identified a cluster of symptoms during the last quarter of the mission including increased fatigue, interpersonal tension, and decreased mood, to name the most common [8, 24, 119–121]. Moreover, one study showed that the third-quarter phenomenon reflected interpersonal hypersensitivity [28]. Palinkas and collaborators [109] found that the third-quarter syndrome was not inherent to environmental factors but was the result of psychosocial factors and mission time awareness. Other authors add that the psychological changes during this period could presuppose the impact of the Antarctic mission or even the anticipation of returning to normal life [109, 122]. Wilson [123] hypothesized that the third-quarter phenomenon could persist until the end of the mission. Kokun and collaborators [124] also showed a major decrease in psychological, performance and health responses in the last two months in ICE/EUE. Consequently, our results confirm the hypothesis that the third-quarter phenomenon could coincide with an anticipatory period as highlighted by Rohrer [27] during the third phase, particularly in the case of long ICE/EUE missions.

4.2. Selection based on psychological abilities

Our study shed light on psychological profiles based on the assessment of mental health at baseline. The OR profile exhibit minors non-psychiatric or psychotic disorders, with scores in the norm of the general population. The HN profile highlights scores out of the norm, with no or very few risk of minors non-psychiatric or psychotic disorders. At baseline, the OR profile perceived higher subjective stress, lower calmness, loss of self-consciousness, cognitive absorption, and decreased performance after get-up compared to the HN profile. Interestingly, no difference was observed in terms of coping flexibility. Winterers are a healthy selected population that needs to fit with ICE/EUE constraints. Maybe, the wintering may not be sufficient to induce differences due to their overall aptitude. Flow experiences have been correlated with salutogenic outcomes [109] and provide active adaptation [125]. One year in Antarctica shows that winterers with a greater prevalence of minors non-psychiatric or psychotic disorders (OR profile) were more impacted by the mission. Compared to the HN profile, they exhibited higher psychological and sensory issues: lower interoceptive (i.e., regulation of psychological distress by paying attention to the body) and present-moment (i.e., acceptation) abilities, higher tiredness and worse performance after wake-up (i.e., notably at the beginning of the winter and during the last quarter of the mission), higher negative affects, tension, lower calmness, a decreased mood and moral feeling, higher perceived and subjective stress. They have a decrease in energy, with a higher level of arousal, a higher level of fatigue that affects performance, a less stable mood, and a higher level of perceived stress. They are less connected to their body sensations and to the present moment.

Their sensory abilities were also impacted by the mission. They had an increase in taste of food, a better hedonic value for olfaction, worse taste abilities, and a higher sensitivity to sound for both ears at 125 Hz. Thus, it appears that the OR profile has a greater hypersensitivity than the HN profile. Since the ambient noise is in the low frequencies, it is possible that individuals develop hypersensitivity on the station. On the DDU station, the noise from the machines that operate the station is still present for some members of the crew. These results confirm to the previous ones we obtained in ICE/EUE [51, 115], we can thus wonder if the evolution of hearing would not be the sense which would allow the most to discriminate the state of stress of the crews. It seems that the more extreme the environment, the more individuals develop a hypersensitivity to auditory stimuli. Consequently, they may pay more attention to the surrounding noise.

Scores within the norm of the general population would therefore not be sufficient to indicate the better good adaptation in ICE/EUE. Our results suggest that the OR profile could be more at risk than the HN profile, which has psychological characteristics considered out of the norm compared to the standard average in the healthy general population with a good health. Our study thus allows us to bring additional elements of answer towards an increase efficient research on the 'right stuff' [126].

The literature has highlighted several factors characteristic of optimal performance (e.g., age, emotional stability, personality traits, coping skills, social compatibility, tolerance with low monotony, performance) [4, 23, 127]. Palinkas et al. [4] highlighted the demand for flexibility and adaptability imposed by ICE/EUE. They stated that the crews likely to be flexible are those that can perform best in these environments. Currently, the selection is not based on a search for profiles that would be the most adaptable. It only looks for aptitude criteria in order to eliminate those individuals who are most at risk of developing psychological maladjustment and clinical decompensation. The aim of screening is therefore to scan an individual's state of health to find critical pathologies at risk of decompensation or non-pre-existing pathologies. However, the discovery or pre-existence of a pathology is not a direct exclusion factor. Certain pathologies that are controlled may be admitted, while those that require regular follow-up or non-stabilized treatment will be excluded (e.g., hypertension, asthma). A psychological examination consisting of questionnaires and an interview with a psychologist allows us to exclude individuals with psychological, psychopathological, behavioral, and addictive disorders that would present a risk during wintering. During this process, the motivations and social skills of the candidates are assessed.

Nevertheless, our results highlight the need to orient the selection towards a search for individuals with 'positive' characteristics (i.e., including coping strategies and optimal psychological resources like strengths level). This would mean disqualifying individuals who would present a risk during the wintering period and selecting candidates with optimal performance characteristics for the greater adaptation. This is the direction that the selection made by the French southern and Antarctic territories should take, and the one recalled by the literature towards which all institutions should aim [23]. There is still a clear need to homogenize both ICE/EUE measurements and selection methods [3]. The GHQ-28 could be a relevant candidate for the further discussions across the countries implied on human adaptation in ICE/EUE environments.

4.3. Recovery processes after one year in Antarctica

Two days have passed since they returned, and winterers seem to be going through a rough time based on their psychophysiological and sensory responses. They have a major decrease in their interoceptive awareness, especially the winterers with the OR profile have more psychological distress during this period compared to the winter peak and the last quarter of the mission. A study onboard a sub-surface ballistic nuclear patrol reported decreased interoceptive awareness during recovery for submariners with a non-adaptive profile based on their cardiac biosignal at baseline compared to those with an adaptive profile [50, 51].

Moreover, they have a higher physiological stress compared to the winter peak. Furthermore, they have a decrease in moral feeling despite an increase in mood and desire to work. The return seems to induce incoherence in the winterers. They seem ambivalent, lost, and not confident about how to cope with the return. Winterers have also a reduction of their level of flow considering their ability to be absorbed in a task (loss of self-consciousness) compared to the winter months and the last quarter of the mission. Therefore, polar stations may generate flow experience. Moreover, the HN profile has a better flow compared to the OR profile during its winterovering. This may be due to their better adaptative abilities in Antarctica. Nevertheless, their ability to be absorbed in a task was greater during the winter months and the last quarter of the mission. Their sensory abilities show that the distant focus of winterers came back to normative values. Also, they decrease their preference for vision towards other senses, increase their taste of food compared to the beginning of the winter and their ability to detect odors compared to the winter months and the last quarter of the mission.

These results even seem to indicate a short-term impact that highlight a difficult return to reality life habits. The short-term recovery may therefore be seen as a new stressor. In 2020, Salam [1] had pointed out that despite the presence of a number of stressors in ICE/EUE, daily life also contained its own stressors. Again, they need to adapt to this environment that they had left for a year. The overall pathogenic impact of the return of overwinterers on psychophysiological and sensory responses may mirrors the overwintering. Nicolas and collaborators [94] reported an association between mature defense, perceived control, and recovery. Therefore, the one year in Antarctica induced a high level of involvement, adaptation to the effects of wintering. Winterer's growth up compared to their departure and learned how to successfully adapt to the harsh of the environment [1, 3, 23]. Long-term salutogenic outcomes were supported by several studies and support that winterers may experience personal growth, self-confidence, meaning of life, health improvement, strength, human values, accomplishment, social skills, ability to deal with stressful situations [1, 3, 7, 23, 128, 129]. This suggests a follow-up need for the winterers, which needs to be longer than 48 hours post mission.

Studies have hypothesized that psychological symptoms may correspond to coping strategies and not necessarily represent a maladaptive syndrome [130, 131]. Coping is a transaction process between an individual's needs and environmental demands [30–32]. The resources available to individuals to cope with stressors will allow the development of pathogenic or salutogenic behavior. A salutogenic behavior requires accepting reality while reacting to their surroundings [132]. Furthermore, they presuppose both interoceptive functioning and MD to operate in an optimal manner. Nevertheless, it might have to evolve over time [23, 133]. In conjunction with individual characteristics, this type of coping would be one of the most predictive of adaptation in extreme environments [23]. More specifically, the use of mature defense mechanisms would contribute to an efficient adaptation in ICE/EUE and be linked to a better recovery [94]. Overall, Le Roy and collaborators [3] highlighted that the coping strategies used in

ICE/EUE were multiple and therefore could not be considered as a stable factor. This conclusion had already been highlighted previously [28]. They are dependent on multiple factors that need to be understood in order to determine the mechanisms that lead to the best adaptation [3].

Our results, combined to those of the literature, underline the complexity of determining temporal patterns of symptomology evolution [33]. Missions in polar regions no longer represent a major risk to crews [95]. Several factors are inherent to this observation: (1) the screening process with a recent search for the most suitable crews; (2) the improvement of living conditions on board the stations. Nevertheless, the search for the best candidates is not enough. It is necessary to determine in parallel which is the best support for a maintenance of the adaptation. Despite the apparent few effects of wintering with the recorded variables, it is essential to provide countermeasures to prepare the return to the mainland at the end of the winter. The recovery period is thus as stressful for the organism as the adaptation required for crews in Antarctica. It would be relevant to study the recovery of winterers over longer periods of time in order to evaluate the recovery and readaptation process. Our results underline that the impact of the return is equivalent for our two profiles, except for a lower level of interoception and flow among the OR profile. Reinforcing interoceptive and mindfulness capacities seem to be an interesting research axis to contribute to improve the adaptive capacities of crews. This could be used during missions to improve recovery. Numerous studies have shown the benefits of mindfulness practice on interoceptive abilities, on the state of stress, emotional regulation, and resilience [134–136]. A neural network has demonstrated an association between a high level of MD and both emotional and interoceptive abilities [50], elements involved in neuroplasticity and therefore adaptive capacities [55]. More recently, a review highlighted its benefits as countermeasures for the next future LDSE [137].

Furthermore, the study of physical activity in our study shows that the level remained stable throughout the wintering period (Supplementary Material). Therefore, no addictive behaviors reflecting a maladaptation syndrome were observed and it does not seem to have an impact on the psychophysiological and sensory responses of the winterers. Nevertheless, it should be noted that all winterers were engaged in regular physical activity. The literature has widely highlighted its benefits in promoting psychological and physical well-being [138–140]. Physical activity practice is an efficient countermeasure in many extreme environments. On board the international space station, daily physical activity helps to limit adverse effects on the physical body functioning [141, 142]. One study highlighted the relevance of physical activity during the MARS500 simulation mission to limit confinement-related psychophysiological deconditioning [143]. Another study supports the hypothesis that physical activity practice at DDU would improve sleep quality [144]. Nevertheless, Martin-Krumm and collaborators [145] found that even if regular physical activity allowed the maintenance of exteroceptive functioning, this was not sufficient to compensate for the thymic degradation induced by the presence of ICE/EUE. The consensus on both pathogenic and salutogenic effects is still an open box in the scientific community. Nevertheless, we can wonder whether the stability observed in the psychophysiological responses of winterers during the wintering months might not be salutogenic. The mechanisms by which they may occur remain an open question, and seem to be related to both environmental characteristics, the type of mission, the profile of the individuals and the characteristics of the group. It remains that a long stay in ICE/EUE is not harmful to the health of the crews. These results provide a new hopeful dynamic for the adaptation of future LDSE. Thus, further research is warranted to better understand typical stress environments to highlight their impact on the human body and behavior, and to understand how humans adapt to them against all odds.

5. Limitations

This study has several methodological shortcomings that are inherent to the ecological environment. The first is the small sample size, an imbalance between male and female, and right- and left-handed subjects. Studying such a population is complex, both in terms of time constraints, and access to infrastructure and personnel (i.e., operational constraints, attendance). This is the reason why we could not have access to all our subjects two days after the return on the continent. They do not come back on the same rotations of the Astrolabe ship. Thus, we chose the rotation including the highest number of subjects. Both the scientific team and participants must be flexible to run such an experiment. Also, the assessment of recovery would be longer. Institutions that organize wintering on bases should help scientific teams to deploy a longitudinal recovery. Secondly, our results are not reproducible beyond the specific experimental conditions and cannot be generalized. Thirdly, effect sizes, ranging from .005 to .451, may be relatively low for some variables. Further studies are therefore needed to confirm our results. Fourth, psychological and interoceptive data (i.e., collected through questionnaires) are subjective measures. Intelligent sensors would provide more objective measures of subjects' adaptation to extreme environments. Fifth, it would have been relevant to use scales developed for ICE/EUE, notably the isolated and confined questionnaire (ICE-Q) developed by Nicolas et al. [146] to measure adaptation in its social, emotional, occupational, physical components; and the mental health checklist that explores the positive adaptation, self-regulation, and anxious apprehension to assess mental health [147]. Finally, RR intervals were recorded testing the Kino® wearable cardiac monitoring device (Heartkinetics, Belgium). The measured ECG signals contained some artifacts that may have impacted their analysis.

6. Conclusion

The present study took place during one year in Antarctica. Results highlight both salutogenic and pathogenic effects. Winterers are able to adapt to this harsh of the environment, and ICE/EUE do not constitute a threat anymore. They notably exhibit positive outcomes during the winter peak. Nevertheless, a third-quarter phenomenon associated with recovery decrements bring us a new vision of life in ICE/EUE. Moreover, two profiles were characterized based on the non-psychotic and minor psychiatric disorders scale: OR profile (i.e., scores within the standard norm of the general population) and HN profile (i.e., few or no psychotic and minor psychiatric disorders). This study underlines that the HN profile is most likely to develop salutogenic adaptive coping and the OR profile more susceptible to inner-exteroceptive and psychological dysfunctions, which could indicate less adapted functioning for long stays in ICE/EUE. Thus, despite increased selection, wintering can impact the psychological and sensory responses of the OR profile. The selection criteria are therefore essential to ensure the greater adaptation during the mission and to allow its higher realization. Moreover, it is crucial to prepare the crews for the return to the mainland because there is no doubt that living in an ICE/EUE wins people's hearts.

7. References

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8. Supplementary Material

Health. None of the single dimension for time (p = .940, BF_{10} = .012), and time*group (p = .426, BF_{10} = .105) reach significance.

Mindfulness disposition. No significant change were found for presence dimension at time (p = .654, BF_{10} = .154), time*group (p = .172, BF_{10} = .165), group (p = .707, BF_{10} = 1.000); and for acceptation dimension at time (p = .159, BF_{10} = 1.000), time*group (p = .425, BF_{10} = .491).

Interoception. None of the differences in the following interoceptive measures reached significance: noticing at time (p = .482, BF_{10} = .244), time*group (p = .461, BF_{10} = .129), group (p = .928, BF_{10} = .536); not distracting at time (p = .456, BF_{10} = .175), time*group (p = .548, BF_{10} = .115), group (p = .291, BF_{10} = .671); not worrying at time (p = .123, BF_{10} = .682), time*group (p = .985, BF_{10} = .337), group (p = .772, BF_{10} = .476); attention regulation at time (p = .273, BF_{10} = .368), time*group (p = .846, BF_{10} = .226), group (p = .577, BF_{10} = .570); emotional awareness at time (p = .243, BF_{10} = .298), time*group

(p = .295, BF_{10} = .163), group (p = .977, BF_{10} = .556); self-regulation at time (p = .642, BF_{10} = .091), time*group (p = .696, BF_{10} = .130); body listening at time (p = .689, BF_{10} = .148), time*group (p = .964, BF_{10} = .113), group (p = .305, BF_{10} = .699); and trusting at time (p = .659, BF_{10} = .115), time*group (p = .530, BF_{10} = .087), group (p = .273, BF_{10} = .884).

Emotion. Positive affect did not change significantly for time (p = .251, BF_{10} = .339), time*group (p = .934, BF_{10} = .205), group (p = .264, BF_{10} = .604); and negative affect for time*group (p = .686, BF_{10} = 1.000).

Thymia. No significant differences were detected for: energy at time (p = .478, BF_{10} = .154), time*group (p = .533, BF_{10} = .138), group (p = .113, BF_{10} = 1.000); tiredness at time*group (p = .176, BF_{10} = .976), tension at time (p = .873, BF_{10} = .001), time*group (p = .798, BF_{10} = .108); and calmness at time (p = .073, BF_{10} = .207), time*group (p = .821, BF_{10} = 1.000).

Sleep quality. None of the following subjective sleep measures reach significance: sleep onset at time (p = .536, BF_{10} = .186), time*group (p = .855, BF_{10} = .066), group (p = .705, BF_{10} = .357); sleep quality at time (p = .387, BF_{10} = .269), time*group (p = .398, BF_{10} = .202), group (p = .118, BF_{10} = .735); sleep arousal at time (p = .427, BF_{10} = .296), time*group (p = .818, BF_{10} = .130), group (p = .305, BF_{10} = .437); performance after getting-up at time (p = .174, BF_{10} = .844); sleep time at time (p = .280, BF_{10} = .325), time*group (p = .574, BF_{10} = .113), group (p = .983, BF_{10} = .345); and time to get-up at time*group (p = .558, BF_{10} = .596), group (p = .132, BF_{10} = .080).

Perceptual energy. Neither of the following measures: desire to work at time*group (p = .371, BF_{10} = .864), group (p = .136, BF_{10} = .146); physical feeling at time (p = .125, BF_{10} = .525), time*group (p = .590, BF_{10} = .342), group (p = .167, BF_{10} = .637); moral at time (p = .707, BF_{10} = .056), time*group (p = .406, BF_{10} = .114); mood at time*group (p = .153, BF_{10} = 1.000) changed significantly.

Subjective stress. Perception of stress did not change significantly at time*group (p = .212, BF_{10} = .547).

Flow. None of the following flow measures reach significance: cognitive control at time (p = .293, BF_{10} = .241), time*group (p = .260, BF_{10} = .257), group (p = .103, BF_{10} = 1.000); Immersion and time transformation at time (p = .715, BF_{10} = .142), time*group (p = .863, BF_{10} = .078), group (p = .389, BF_{10} = .548); loss of self-consciousness at time (p = .607, BF_{10} = .120), time*group (p = .992, BF_{10} = .138), group (p = .108, BF_{10} = 1.000); autotelic experience at time (p = .702, BF_{10} = .149), time*group (p = .513, BF_{10} = .088), group (p = .492, BF_{10} = .587); cognitive absorption at time (p = .902, BF_{10} = .073), time*group (p = .876, BF_{10} = .110), group (p = .082, BF_{10} = 1.000).

Team cohesion. None of the shared interactions with pairs at time (p = .262, BF_{10} = .362), time*group (p = .139, BF_{10} = .174), group (p = .606, BF_{10} = .482) or towards the leader at time*group (p = .668, BF_{10} = .395), group (p = .652, BF_{10} = .111) changed significantly.

Sensory evaluation. None the following measures changed significantly: olfaction for time (p = .445, BF_{10} = .210), time*group (p = .121, BF_{10} = .100), group (p = .629, BF_{10} = .469); taste for time (p = .943, BF_{10} = .090), time*group (p = .644, BF_{10} = .043), group (p = .557, BF_{10} = .484); posture for time (p = .829, BF_{10} = .113), time*group (p = .378, BF_{10} = .056), group (p = .667, BF_{10} = .496); touch for time (p = .937, BF_{10} = .096), time*group (p = .891, BF_{10} = .036), group (p = .923, BF_{10} = .374); vision for time*group (p = .936, BF_{10} = .174), group (p = .403, BF_{10} = .578); and hearing for time (p = .061, BF_{10} = 1.000), time*group (p = .792, BF_{10} = .472), group (p = .685, BF_{10} = .332).

Subjective exteroceptive acuity. None of the following measures changed significantly: vision for time*group (p = .225, BF_{10} = .373), group (p = .230, BF_{10} = .502); hearing for time*group (p = .817, BF_{10} = .470), group (p = .698, BF_{10} = .070); olfaction for time (p = .202, BF_{10} = .389), time*group (p = .756, BF_{10} = .199), group (p = .597, BF_{10} = .511); taste for time*group (p = .829, BF_{10} = .776), group (p = .176, BF_{10} = .334); touch for time (p = .159, BF_{10} = .360), time*group (p = .071, BF_{10} = .163), group (p = .935, BF_{10} = .433); and posture for time (p = .600, BF_{10} = .139), time*group (p = .728, BF_{10} = .078), group (p = .270, BF_{10} = .547).

Appetite. No significant differences were detected for: level of appetite at time*group (p = .771, BF_{10} = .629), group (p = .332, BF_{10} = .002); satiety at time (p = .528, BF_{10} = .218), time*group (p = .791, BF_{10} = .088), group (p = .745, BF_{10} = .404); taste of food at time*group (p = .110, BF_{10} = 1.000); hunger at the beginning of meals at time (p = .260, BF_{10} = .395), time*group (p = .972, BF_{10} = .203), group (p = .762, BF_{10} = .505); hunger outside meals at time (p = .884, BF_{10} = .098), time*group (p = .981, BF_{10} = .052), group (p = .726, BF_{10} = .511); number of meals per day at time*group (p = .274, BF_{10} = .203), group (p = .531, BF_{10} = .505).

HRV. RR intervals at time*group (p = .362, BF_{10} = .618), group (p = .267, BF_{10} = .038); SDNN at time (p = .543, BF_{10} = .169); time*group (p = .028, BF_{10} = .095), group (p = .553, BF_{10} = .553); RMSSD at time (p = .858, BF_{10} = .183), time*group (p = .116, BF_{10} = .082), group (p = .781, BF_{10} = .447); pNN50 at time (p = .368, BF_{10} = .441), time*group (p = .269, BF_{10} = .191), group (p = .828, BF_{10} = .438); LF peak at time (p = .214, BF_{10} = .578), time*group (p = .631, BF_{10} = .341), group (p = .127, BF_{10} = .589); HF peak at time (p = .455, BF_{10} = .455), time*group (p = .202, BF_{10} = .239), group (p = .588, BF_{10} = 1.294); LF abs at time (p = .799, BF_{10} = .164), time*group (p = .041, BF_{10} = .108), group (p = .377, BF_{10} = .654); HF abs at time (p = .561, BF_{10} = .182), time*group (p = .156, BF_{10} = .084), group (p = .527, BF_{10} = .456); LF/HF ratio at time (p = .498, BF_{10} = .716), time*group (p = .789, BF_{10} = .288), group (p = .261, BF_{10} = 1.235); SD1 at time (p = .858, BF_{10} = .185), time*group (p = .116, BF_{10} = .085), group (p = .781, BF_{10} = .442); SD2 at time (p = .470, BF_{10} = .176), time*group (p = .022, BF_{10} = .105), group (p = .532, BF_{10} = .572); SD ratio at time (p = .231, BF_{10} = 1.216), time*group (p = .282, BF_{10} = .502), group (p = .408, BF_{10} = .923); $\alpha 1$ at time (p = .134, BF_{10} = .959), time*group (p = .883, BF_{10} = .562), group (p = .264, BF_{10} = .557); $\alpha 2$ at time (p = .791, BF_{10} = .154), time*group (p = .065, BF_{10} = .078), group (p = .412, BF_{10} = .517); and sample entropy at time (p = .858, BF_{10} = 1.517), time*group (p = .651, BF_{10} = .478), group (p = .644, BF_{10} = .765) did not change significantly.

Olfaction. No significant change was found for detection at time (p = .149, BF_{10} = 1.000), time*group (p = .467, BF_{10} = .680), group (p = .139, BF_{10} = .589); identification at time (p = .841, BF_{10} = .122), time*group (p = .710, BF_{10} = .153), group (p = .084, BF_{10} = 1.000); and hedonic value at time (p = .836, BF_{10} = .012), time*group (p = .467, BF_{10} = .166).

Vision. Neither of the following measures: close focus at time (p = .241, BF_{10} = 1.000), time*group (p = .479, BF_{10} = .491), group (p = .604, BF_{10} = .003); and distant focus at time*group (p = .171, BF_{10} = .298), group (p = .843, BF_{10} = .642) changed significantly.

Hearing. No significant change was found for both the left and the right ear For the *left ear*, frequencies concerned are 125 Hz at time (p = .339, BF_{10} = .081), time*group (p = .671, BF_{10} = .321; 500 Hz LE at time (p = .143, BF_{10} = .867), time*group (p = .817, BF_{10} = .910), group (p = .092, BF_{10} = 1.000); 1000 Hz LE at time (p = .295, BF_{10} = .302), time*group (p = .416, BF_{10} = .214), group (p = .398, BF_{10} = .695); 2000 Hz LE at time (p = .335, BF_{10} = .377), time*group (p = .845, BF_{10} = .196), group (p = .398, BF_{10} = .514); 4000 Hz LE at time (p = .112, BF_{10} = .793), time*group (p = .930, BF_{10} = .552), group (p = .492, BF_{10} = .684); 6000 Hz LE at time (p = .437, BF_{10} = .319), time*group (p = .874, BF_{10} = .251), group (p = .274, BF_{10} = .794); 8000 Hz LE at time (p = .082, BF_{10} = .557), time*group (p = .151, BF_{10} = .294), and group (p = .620, BF_{10} = .510). For the *right ear*, frequencies concerned are 125 Hz at time*group (p = .179, BF_{10} = 1.000); 500 Hz at time (p = .264, BF_{10} = .545), time*group (p = .264, BF_{10} = .423), group (p = .150, BF_{10} = .733); 1000 Hz at time*group (p = .240, BF_{10} = .467), group (p = .659, BF_{10} = .117); 2000 Hz at time (p = .149, BF_{10} = 1.000), time*group (p = .100, BF_{10} = .562), group (p = .248, BF_{10} = .457); 4000 Hz at time*group (p = .314, BF_{10} = .841), group (p = .221, BF_{10} = .118); 6000 Hz at time (p = .511, BF_{10} = .362), time*group (p = .050, BF_{10} = .257), group (p = .221, BF_{10} = .747); and 8000 Hz at time (p = .247, BF_{10} = .545), time*group (p = .611, BF_{10} = .351), group (p = .725, BF_{10} = .600).

Taste. Taste abilities did not change significantly at time (p = .758, BF_{10} = .067), and time*group (p = .297, BF_{10} = .171).

Physical activity. Physical activity practice does not reach significance at time (p = .919, BF_{10} = .094), time*group (p = .812, BF_{10} = .041), and group (p = .607, BF_{10} = .426).

Synthèse des résultats principaux

L'étude ISHOW avait deux objectifs principaux : (1) investiguer l'impact d'un séjour d'un an en Antarctique sur les réponses psychologiques, physiologiques et sensorielles ; et (2) évaluer la récupération de cette expérience dans le post-immédiat, soit deux jours après le retour sur le Continent.

Ainsi, malgré une endurance d'une année d'isolement sur le continent blanc de l'Antarctique, nos résultats mettent en évidence des effets positifs et négatifs. Ils démontrent que les hivernants ont été capables de s'adapter, notamment durant le pic du mois d'hiver. Cependant, le phénomène du troisième quart a pu être souligné et associé à une altération de la récupération. Par conséquent, l'adaptation n'est pas un phénomène linéaire et le retour sur le continent constitue un enjeu adaptatif aussi important que l'arrivée en Antarctique.

Cette étude poursuivait également l'objectif d'explorer le rôle de l'état de santé avant la mission sur les réponses pendant et après la mission. La prise en compte de deux profils basés sur le score à l'échelle du « general health questionnaire », échelle utilisée en santé pour dépister les troubles non-psychiques et psychiatriques mineurs, a montré des capacités d'adaptation différentes de ces deux profils. Le profil d'hivernants ne présentant aucun trouble au départ montre globalement un profil plus protecteur que le profil présentant quelques symptômes mineurs. Ces résultats soulignent l'enjeu de la sélection avant le départ chez des individus globalement en bonne santé et suggèrent que l'évaluation subjective de la santé psychique par le professionnel est un indicateur d'intérêt d'adaptation des équipages à la mission de longue durée.

Synthèse du chapitre II

L’objectif de ce deuxième chapitre expérimental était d’évaluer l’impact des environnements analogues à l’espace en termes de caractéristiques ICE/EUE sur des sujets naïfs (ENACT, RAD’LO) et professionnels (ANTIDOTE, SSBN, ISHOW) afin de mieux appréhender l'adaptation psychologique, cognitive, physiologique, sensorielle et comportementale à ces contraintes.

Ce chapitre découpé selon les contraintes du milieu offre un panorama allant d’un voyage court impliquant des stimulations gravitaires répétées (ENACT) à des situations extrêmes (ANTIDOTE, RAD’LO) en passant par le déroulé d’un voyage spatial intégrant le trajet (SSBN) et la mission sur base-vie (ISHOW). Ce panorama pointe des marqueurs d’intérêt de l’adaptation aux environnements ICE/EUE, parmi lesquels le PNS indexé par la HRV.

Nos résultats mettent en évidence un impact plus ou moins délétère, en fonction des caractéristiques du milieu, des réponses psychologiques, physiologiques, cognitives et extéroceptives avec une sensibilité plus marquée lors du troisième quart de mission. Également, ils ont mis en lumière la nécessité de mesurer la période de récupération. Celle-ci constitue une phase critique qui requiert une attention particulière, notamment parce que l’état psychologique continue à se dégrader ainsi que les réponses intéro- et extéroceptives. Notre dernière étude soulève qu’elle pourrait résulter d’un nouvel enjeu d’adaptation.

L’adaptation est une notion complexe et multifactorielle dont l’étude est croissante dans les ICE/EUE. Elle sous-entend l’implication de processus cognitifs, émotionnels, physiologiques et sensoriels pour maintenir l’organisme à un état homéostasique et donc d’équilibre au cours du temps. Les capacités d’adaptation ne sont pas non plus identiques et peuvent différer en fonction du profil des individus. En conséquence, elles sont propres à chacun et dépendantes du niveau de ressources à disposition. Elles sont aussi amenées à évoluer au cours de la mission. Du fait de son interaction avec le monde, un individu n’emploiera pas nécessairement les mêmes moyens pour faire face au stress perçu et vécu par l’organisme. Cette flexibilité du cerveau est contributive de cet état adaptatif.

Cibler les individus étant les plus à risque et ceux étant à même de maintenir leur adaptation est primordial pour les futurs LDSE. Nos résultats ont souligné l'implication du PNS comme facteur de protection contre les effets néfastes de l'environnement et l'enjeu de la sélection des profils les plus adaptables fondés sur l'évaluation par questionnaires des troubles non-psychiques et psychotiques mineurs. Ces deux éléments pris dans leur ensemble font appels à des processus de régulation intero- et extéroceptifs, dont l'étude s'accélère ces dernières années. Ils orientent les recherches vers l'étude de contre-mesures visant à les renforcer. De nombreuses contre-mesures ciblant ces régulations sont actuellement étudiées par la littérature (Le Roy et al., 2023). Toutefois, un travail de recherche est encore nécessaire pour évaluer leurs pertinences en contexte écologique et permettre de mieux appréhender leur intérêt pour limiter les effets pathogènes des missions spatiales.

La question de ces enjeux est couverte par le chapitre suivant dont l'objectif est de caractériser des profils d'adaptation et proposer des contre-mesures aux sujets les plus à risque au moyen des dernières avancées médicales et technologiques. L'enjeu, *in fine*, est bien celui de maintenir des conditions opérationnelles optimales et d'assurer la santé des membres de l'équipage.

CHAPITRE III

Contre-mesures médicales : Enjeu de santé en vue des prochains longs voyages dans l'espace

Il m'est soudain apparu que ce petit pois,
joli et bleu, était la Terre.
J'ai levé mon pouce et j'ai fermé un œil,
et mon pouce a effacé la planète Terre.
Je n'avais pas l'impression d'être un géant.
Je me sentais très, très petit

Neil Armstrong

Ces dernières années, de nombreuses études se sont intéressées aux mécanismes expliquant les processus de monitoring et de régulation entre le cerveau et le corps pour apporter des propositions d'intervention de prévention de la santé. La cible des interactions corps-cerveau est également un enjeu de maintien/renforcement de l'adaptation aux situations stressantes chez le sujet sain. Cette deuxième partie expérimentale s'inscrit dans ce cadre. Plus précisément, elle se propose d'une part de valider l'importance de ce cadre théorique chez des sujets neurotypiques soumis à des contraintes opérationnelles de type environnement isolé et confiné (*isolated and confined environment,* ICE) et environnement extrême et inhabituel (*extreme and unusual environment*, EUE), le plus souvent dans l'exercice de leur métier. D'autre part, elle s'attache à évaluer des pistes innovantes visant les interactions corps-cerveau pour les professionnels des environnements analogues spatiaux.

Études de validation du cadre théorique

Deux études organisent cette première partie. Elles s'attachent à mieux appréhender les relations entre les acteurs de l'axe corps-cerveau que sont l'intéroception, le fonctionnement parasympathique et l'extéroception en intégrant la capacité du sujet à être en pleine conscience (disposition *mindfulness*).

Les liens entre le cerveau et le corps sont bidirectionnels. Les voies afférentes intègrent les informations internes du corps et envoient ces signaux au système nerveux central (*central nervous system*, CNS ; i.e., système de régulation interne responsable de l'interprétation et de l'intégration de des signaux concernant l'état du corps essentiel à la survie) pour évaluation et ajustement de l'état corporel. Les voies efférentes désignent la communication entre le cerveau et les organes corporels. Par conséquent, le réseau intéroceptif mobilise de nombreuses régions cérébrales qui incluent le cortex insulaire, le cortex cingulaire, le gyrus frontal inférieur, et le cortex sensorimoteur. Ces structures projettent elles-mêmes sur d'autres structures impliquées dans les processus de régulation psychologique, cognitif, physiologique et sensorielle. Les signaux sont ainsi encodés de façon multimodale via des voies intéroceptives mais également extéroceptives (i.e., visuels, vestibulaires, somatosensoriels) vers des récepteurs périphériques.

L'intéroception se réfère à l'ensemble des processus par lesquels le système nerveux perçoit, interprète, intègre et régule les signaux qui proviennent de l'état interne du corps (e.g., cardiovasculaire, gastrointestinal, respiratoire), et qui renseignent sur son état homéostasique. Sa dimension multifactorielle inclut : la précision intéroceptive (i.e., perception et détection des signaux provenant du *inner body* tels que les battements du cœur), la sensibilité intéroceptive (i.e., évaluation subjective des signaux intéroceptifs) et la conscience intéroceptive (i.e., le produit métacognitif de la précision et sensibilité intéroceptive). Tandis que la précision intéroceptive est mesurée par une tâche de détection cardiaque, la sensibilité intéroceptive est évaluée par questionnaires (e.g., MAIA) et influencée par des processus cognitifs efférents (i.e., *top-down*). Khalsa et al. (2018) ont mis en évidence son rôle dans divers systèmes corporels. L'intéroception est notamment impliquée dans l'auto-régulation, la gestion émotionnelle et de stress, les fonctions cognitives de haut niveau et la conscience (Critchley & Garfinkel, 2017 ; Khalsa et al., 2018 ; Quadts et al., 2018 ; Schulz & Vögele, 2015 ; Seth et al., 2012 ; Tsakiris & Critchley, 2016). La qualité de l'intéroception modulerait les émotions pour ajuster sa réponse comportementale aux demandes de l'environnement (Khalsa et al., 2018). L'intéroception constituerait le système permettant d'ajuster les processus multimodaux de régulation afférents et efférents. Notre représentation du monde dépend ainsi non seulement de la perception des informations du milieu interne au corps (e.g., viscères) mais également de la perception des informations en provenance du milieu extérieur (e.g., vision, ouïe), soit de l'environnement, remise à jour à chaque instant (Gibson, 2019). De plus, l'intéroception constituerait un des mécanismes primaires de la capacité à s'inscrire dans l'instant présent, notamment via l'insula (Di Lernia et al., 2018).

L'extéroception est définie comme la perception et l'intégration des signaux provenant de l'environnement par le corps (e.g., vision, audition, olfaction, goût, proprioception) et renseigne sur la position du corps dans l'espace. Ces deux voies retranscrivent une organisation hiérarchisée selon trois niveaux en impliquant des structures situées au niveau de la moelle épinière, du tronc cérébral et des aires corticales. De plus, elles sont utilisées par le CNS pour maintenir l'organisme à l'état d'équilibre et établir une représentation du monde entre le milieu interne et externe. Un nombre croissant d'études a montré un lien entre les habilités intéroceptives et extéroceptives. Plus spécifiquement, l'olfaction, qui nous aide à interpréter l'importance des stimuli externes environnants, détermine une grande partie de l'expérience humaine, notamment émotionnelle. La recherche dans ce domaine révèle des relations importantes entre l'odorat et de nombreux aspects du processus psychologique impliquant l'adaptation humaine (Weir, 2011). Plusieurs auteurs suggèrent que les odeurs ont la capacité de moduler l'humeur, la cognition et le comportement chez les individus (Stevenson, 2013). Une relation étroite existe entre le traitement de l'information olfactive et affective, soulignée par des structures cérébrales communes (e.g., amygdale, hippocampe, insula, cortex cingulaire antérieur, cortex orbitofrontal) (Soudry et al., 2011). Plus récemment, Toet et al. (2020) ont montré un lien entre la valence de l'émotion et les odeurs dans une population de sujets neurotypiques.

Si un meilleur niveau d'intéroception a été associé à de nombreux *positive outcome*s dans la santé (Khalsa et al., 2018), parallèlement, le fonctionnement vagal indexé par la variabilité de la fréquence cardiaque (*hear rate variability*, HRV) a été proposée comme un marqueur d'adaptation et un modulateur central des fonctions régulatrices. Les études se focalisant sur les régulations de l'ANS ont souligné qu'une faible HRV était associée à des troubles psychologiques (e.g., stress, dépression, anxiété), des pathologies majeures (e.g., cancers), permet de prédire l'émergence d'évènements cardiovasculaires (e.g., infarctus) et est ainsi en lien avec une augmentation de la mortalité. A l'inverse, un niveau élevé de HRV est associé à de meilleures capacités de gestion du stress, une meilleure santé, de meilleures performances cognitives (e.g., fonctions exécutives), une meilleure régulation émotionnelle. Une activation parasympathique élevée au repos a été associée à une régulation sympathique ajustée en situation de contrainte et est ainsi associée un meilleur fonctionnement de l'organisme. La littérature l'étudie notamment au repos sous l'indicateur temporel de la moyenne quadratique des differences successives entre intervalles RR adjacents (*root mean square of differences between adjacent RR intervals*, RMSSD). Également, des études ont montré que des niveaux intéroceptifs et parasympathiques élevés étaient associés à de meilleures capacités de régulation émotionnelle. Le maintien homéostasique dépend à la fois de la bonne perception des modifications en provenance du milieu extérieur et de la perception correcte des impacts que ces changements ont sur l'intéroception. En outre, la littérature a mis en évidence que l'intéroception serait la composante sensorielle et l'ANS via la mesure de la HRV, la sortie primaire de cet état d'équilibre. Les communications entre les réseaux intéroceptifs et l'ANS reposent sur un réseau de connexions étagées. Les signaux intéroceptifs sont transmis au CNS par l'intermédiaire de deux ganglions sensoriels périphériques en provenance de deux voies afférentes ou neuronales périphériques ascendantes distinctes. Les ganglions issus des voies crâniennes et vagales projettent des informations (e.g., signaux mécano-, thermo-, chimiorécepteurs ou métaborécepteurs) vers le noyau du tractus solitaire (*nucleus tractus solitarius*, NTS) du tronc cérébral, ce sont les afférences parasympathiques du système nerveux parasympathique (*parasympathetic nervous system*, PNS). Les ganglions de la racine dorsale issus de la voie nerveuse spinale projettent des informations (e.g., signaux liés à la température, à la douleur et aux lésions tissulaires) vers le cerveau par l'intermédiaire de la moelle épinière, ce sont les afférences sympathiques du SNS. De plus, l'implication des composantes intéroceptives et de HRV dans le stress physiologique serait médiée par des processus de contrôle exécutif pilotés par des changements d'activité dans les régions préfrontales et (para-)limbiques cérébrales via le cortex cingulaire antérieur et l'insula.

La prise en compte des informations intéroceptives instant après instant a été décrite comme plus ajustée chez les sujets à disposition mindful (*mindful disposition*, MD) ou devenu mindful par la pratique de la méditation. La qualité de la *mindfulness* a été associée à une meilleure santé physique et mentale ainsi qu'à une meilleure réponse de stress tant sur le plan psychologique que physiologique. Il a également suggéré que les sujets ayant un fonctionnement *mindfulness* élevé disposeraient de compétences proprioceptives différentes (Verdonk et al., 2022) laissant suggérer que l'ensemble du fonctionnement extéroceptif pourrait fonctionner différemment entre les sujets en fonction de leur fonctionnement mindful. Enfin, les sujets caractérisés par un haut fonctionnement mindful auraient une réponse autonome plus ajustée aux stresseurs, notamment une meilleure flexibilité parasympathique (Pinna & Edward, 2020). Aussi, le fonctionnement mindful participerait aux mécanismes impliqués dans l'impact d'un environnement appauvri sensoriellement, comme le sont les environnements ICE en soutenant une réponse adaptée pour le maintien de la santé. Il serait également impliqué dans les mécanismes de réponse adaptée aux situations de stress aigu qui pourraient subvenir lors des missions spatiales de longue durée. Une partie des travaux de la partie précédente a porté sur la sensibilité intéroceptive et la MD au sens trait de personnalité, c'est-à-dire une capacité stable pour un individu de percevoir les signaux provenant du milieu interne du corps instant après instant, et sans jugement. Il est à préciser qu'il s'agit dans ce cadre d'une disposition, c'est-à-dire la « capacité d'un individu à être mindful dans la vie de tous les jours en l'absence de tout d'entraînement à la *mindfulness* » (Brown & Ryan, 2003).

Dans ce cadre, un premier travail, étude NEURAL NETWORKS, s'est attachée à explorer les relations entre intéro- extéroception, trait *mindfulness*, et émotions chez des professionnels exerçant en environnement ICE. Cette étude avait trois objectifs principaux : (1) établir un réseau d'interactions causales entre les variables intéroceptives, olfactives, émotionnelles et de fonctionnement *mindfulness* (MD) ; (2) investiguer si la MD est associée à un haut niveau d'intéro- extéroception et à des émotions positives ; et (3) évaluer comment la MD interagit avec les autres variables susmentionnées en employant la méthodologie des réseaux d'interactions causales. Dans cette étude, l'olfaction a été privilégiée au regard de son rôle dans la réponse émotionnelle (Soudry et al., 2011). En effet, les signaux olfactifs sont traités dans des régions du cerveau (e.g., amygdale, hippocampe) impliquées dans la régulation des émotions. Une étude a mis en évidence sur un échantillon de 67 individus une association entre les odeurs corporelles et la valence émotionnelle (Chen & Haviland-Jones, 2000).

Nous posons l'hypothèse qu'il existe des relations réciproques entre les processus intéro-extéroceptifs, la MD et la valence des émotions, et que celles-ci diffèrent selon la MD avec des niveaux et des connections plus importants entre l'intéroception, l'olfaction et les émotions positives pour le profil haut MD comparativement au profil bas MD

Mindfulness, Interoception, and Olfaction: A Network Approach

Publié[12]

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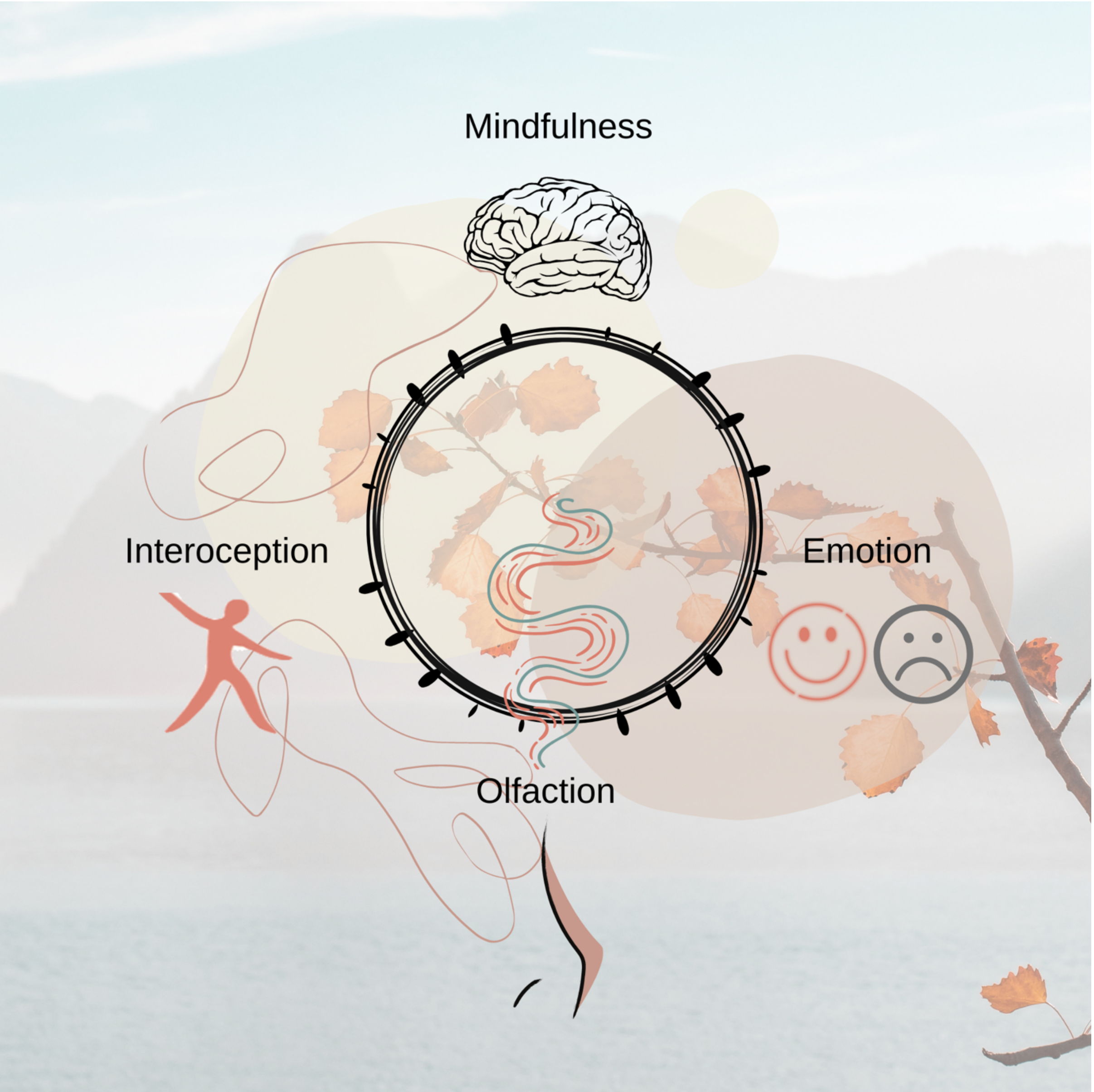
Abstract

The fine-tuned interplay between the brain and the body underlies the adaptive ability to respond appropriately in the changing environment. Mindfulness Disposition (MD) has been associated with efficient emotional functioning because of a better ability to feel engaged by information from the body and to notice subtle changes. This interoceptive ability is considered to shape the ability to respond to external stimuli, especially olfaction. However, few studies have evaluated the relationships between interoception and exteroception according to MD. We conducted an exploratory study among 76 healthy subjects for first investigating whether MD is associated with better exteroception and second for describing the causal interactions network between mindfulness, interoception, emotion, and subjective and objective olfaction assessments. Results found that a high level of MD defined by clustering exhibited best scores in positive emotions, interoception, and extra sensors' acuity. The causal network approach showed that the interactions between the interoception subscales differed according to the MD profiles. Moreover, interoception awareness is strongly connected with both the MD and the hedonic value of odors. Then, differences according to MD might provide arguments for a more mindful attention style toward interoceptive cues in relation to available exteroceptive information. This interaction might underlie positive health.

Figure 22
Graphical abstract NEURAL NETWORKS



Keywords

Causal network, Clustering, Interoception, Mindfulness, Olfaction

1. Introduction

We constantly act upon the world while our brain continuously integrates information from inside and outside the body. Through the body, the brain receives information about the state of the external world (exteroception) and the body's physiological state (interoception) [1]. The fine-tuned interplay between the brain and the body underlies the adaptive ability to respond appropriately in a constantly changing environment. It refers to an efficient body awareness which is the individual's ability to feel engaged by information from the body and to notice subtle changes [2].

Furthermore, the construction of body awareness refers to a particular kind of mindful, non-judgmental awareness and a sense of self, grounded in physical external as internal sensations in the present moment [3]. Such an assertion contradicts the usual conceptualization in the medical and psychological literature. Body awareness has been mainly investigated in studies of psychiatric disorders as a cognitive attitude characterized by « an exaggerated patient focus on physical symptoms, magnification (« somatosensory amplification »), rumination, and beliefs of catastrophic outcomes » [2]. However, accumulated evidence supports the clinical benefits of body awareness [4]. Findings from numerous studies suggest the interest of improving body awareness in the management of chronic diseases including somatic [5–7] and psychiatric chronic diseases [8,9], as of chronic pain [10].

Thus, one of the challenges for health is to identify individual psychological resources associated with an efficient body awareness that can be developed. One pertinent candidate could be the Mindfulness Disposition (MD), which characterizes the awareness that emerges by paying attention on purpose, in the present moment, and non-judgmentally to the unfolding experience that is moment by moment [11,12]. Whether MD has been conceptualized as a stable ability to be mindful in everyday life, regardless of events [13], it is developed by mindfulness intervention [11,14]. This disposition has been associated with various positive physical and psychological health and with protective functioning (e.g., positive psychology, improvement of the quality of life) for both healthy subjects and patients [14–16]. More precisely, MD has been associated with resilience and its maintenance through attentional abilities, psychological flexibility, and efficient emotional regulation [16,17] that contribute to reduced perceived stress [18,19].

Furthermore, MD has been proposed to be associated with effective interoception. That is an efficient perception of the body from the inside that contributes to the regulation of physiological integrity (homeostasis) and the associated affective feelings, drives, and emotions. On one hand, MD has been positively related to a high level of interoceptive sensibility as assessed with the Multidimensional Assessment of Interoceptive Awareness questionnaire (MAIA) [3,20–23]. On the other hand, however, some work has reported mixed evidence of the association between mindfulness and interoception accuracy (mostly in using the heartbeat tracking paradigm) [24–29]. Overall, it has been proposed that MD is positively linked to interoceptive awareness [23]. This positive association is implicated in the benefits of MD in emotion regulation and cognition [17].

However, it is curious to note that no studies have investigated exteroception (i.e., the perception of surrounding stimuli through the classical sensory organs) in the MD. Yet, we are aware that the integration of multimodal exteroceptive signals (e.g., vision, sound, touch, olfaction, taste), vestibular and proprioceptive systems, and voluntary motor systems contribute to the exteroceptive body awareness (or « body schema »). Moreover, dysfunctions in exteroception impact patients' body experience and functionality [30–33]. This implicit knowledge that we have of our body in relation to space and movement is in fact related to interoceptive body awareness [34]. Together, the interoception and exteroception body awareness emphasize the internal representation we have of our body and posture in relation to the environment [35]. Whether they have an impact on each other to guide action, the interoceptive ability is considered to shape the ability to respond to external stimuli over the long term [36].

This interaction is highlighted by studies using neuroimagery, which have shown the key role of the insular cortex in the integration of multimodal information and in interoceptive and exteroceptive processing [36]. Then, studies in chemosensory domains show that the central dorsal insula presents a chemosensory overlap of gustatory and olfactory sensations [37]. With respect to olfaction, a negative relationship between cardiac interoceptive accuracy and olfactory functioning (assessed by detection threshold, odor discrimination, and odor identification) has also been found [38]. Olfaction is an integral part of daily life, from deciding what to eat [39] to recalling autobiographical memories [40], or even choosing a partner [41]. As one of our five senses (i.e., sight, hearing, smell, taste, touch), it helps interpret the salience of surrounding external stimuli and determines much of the human experience. Olfactory research reveals important relationships between the sense of smell and many aspects of the psychological process involving human adaptation [42]. First, many studies suggest that odors can modulate mood, cognition, and behavior in healthy subjects [43]. Furthermore, stress can affect the olfactory detection threshold of a malodor, suggesting a close relationship between stress-related sensory hypervigilance and the olfactory system [44]. Second, this close relationship between olfactory and affective information processing is highlighted both by the incidence of major depression in anosmic subjects [45] and the importance of olfactory disorders in the case of mood disorders [46].

Overall, these findings suggest a situational interaction of intero- and exteroceptive stimulus processing that may depend on MD and extend to emotional states. However, to our knowledge, few studies have evaluated the relationships between interoception, exteroception, and emotion in healthy subjects, and even fewer their causal interactions. Verdonk et al. [17] reviewed the Event-Related Potential (ERP) literature related to mindfulness for a better understand of how mindfulness works. The review suggests that mindfulness would facilitate the conscious processing of information that comes from inside and outside the body. Unfortunately, the existing ERP literature does not allow for hypotheses to be formulated on the causal interaction network between mindfulness, interoception, exteroception, and emotion. There are several models for studying causal interactions. A causal interaction model is a set of mechanisms, a set of causes, and an effect. It relaxes the restrictions of causal independence models in which each cause has a unique mechanism variable, and each mechanism variable has a unique cause [47]. For example, a causal interaction model is relevant for conceptualizing a mental disorder as resulting from causal interactions network between symptoms, rather than as an underlying pathological entity [48]. Psychiatric symptoms have been argued as reciprocal rather than common cause effects. Then, disorders are studied using a network approach to evaluate the network of symptoms (« nodes ») presumed to be causal and the connections between them (« edges ») [48]. Such a causal interaction model could provide a way to investigate the network of causal relations between interoception, exteroception, emotion, and mindfulness, functioning as systems of interacting variables.

In this paper, we aim to evaluate the relationship between MD, interoception, exteroception, and emotion using three questions. The first issue is concerned with the causal interactions network between mindfulness, interoception, exteroception, and emotion. We make the hypothesis that reciprocal relationships exist between them. The second issue will part in a categorical approach focusing on whether the MD is associated with differential interoception, exteroception, and emotion. Our hypothesis is that subjects with MD exhibited a higher level of interoception, exteroception including olfaction and emotion. The third aims to evaluate how MD interacts with interoception, olfaction, and emotion using a causal network approach. We assume that the network of causal relations differs according to the MD profile, with more connections among interoception, olfaction, and positive emotion for high MD groups.

2. Materials and methods

2.1. Participants and design

The sample included 76 civilians and military scheduled for a marine, submarine, or polar overwintering a few weeks later. They took part in an exploratory pragmatic study aiming to evaluate the impact of isolated and confined environments on human adaptation. The baseline was realized during the autumn season of 2017–2018 for the sailors and during the autumn season of 2018–2019 for the polar winterers. See Table 1 for demographic information. The follow-up of the cohort is yet in progress.

Table 1

Characteristics of participants for each Mindfulness Disposition (MD) cluster (mean ± standard deviation or sample size)

Sociodemographic Data	MD Cluster on All Participants (n = 76)		MD Cluster on ETOC Subsample (n = 31)		
	High MD	Low MD	High MD	Low MD	p-value*
N	32	44	18	13	
Age	27 ± 5.59	30 ± 10.27	25 ± 4.91	30 ± 10.15	.56
Woman/man	4/28	8/36	2/16	0/13	.38
Submariners	17	11	8	6	
Marines	8	4	8	3	
Overwinterers	7	29	2	4	

*p-value for analysis of unit and Chi2 cluster effect calculated for age and gender. None of the measures had a significant cluster effect.

The study has been approved by the Comité de Protection des Personnes sud-est VI (France) in September 2017 (ID-RCB: 2017-A01329-44). After a complete description of the study, written informed consent for participation in this low-risk study was obtained.

2.2. Measures

The collected socio-demographic included: age, gender, marital status, submarine experience, position occupied in the Sub-Surface Ballistic Nuclear (SSBN).

The auto-questionnaire used to assess mindful status was the Freiburg Mindfulness Inventory (FMI, 14 items) (Supplementary Figure S1). It measures dispositional trait mindfulness by indexing facets of Presence and Non-judgmental acceptance. It is semantically independent of a meditation context and it is applicable to all population groups, in particular those with no practice of mindfulness meditation. It is scored using a four-point scale, with responses ranging from 1 (rarely) to 4 (almost always). A total mindfulness score was computed by summing items except for the 13th item, which was reversed [49,50].

Interoceptive awareness was evaluated using the 32-item MAIA questionnaire (multidimensional assessment of interoceptive awareness) (Supplementary Figure S2) [3] that measures eight facets: (i) Noticing (awareness of uncomfortable, comfortable, and neutral body sensations), (ii) Not-Distracting (tendency to ignore or distract oneself from sensations of pain or discomfort), (iii) Not-Worrying (emotional distress or worry with sensations of pain or discomfort), (iv) Attention Regulation (ability to sustain and control attention to body sensation), (v) Emotional Awareness (Awareness of the connection between body sensations and emotional states), (vi) Self-Regulation (ability to regulate psychological distress by attention to body sensations), (vii) Body Listening (actively listens to the body for insight), and (viii) Trusting (experiences one's body as safe and trustworthy). This questionnaire considers the adaptive aspects of body awareness (i.e., as a present-moment and attention style to body sensations), which contrast with anxiety-driven hypervigilance to body sensations [2]. It is scored using a six-point scale, with 5 responses ranging from 0 (never) to 5 (always).

Emotional functioning was assessed using the scale of positive and negative emotional experiences (Scale of Positive and Negative Experience, SPANE) (Supplementary Figure S3) [51,52], including 12 items to be rated by the subject on a five-point Likert scale (1 = very rarely or practically never, to 5 = very often or always). The latest passed week was considered.

For exteroception, we used a homemade questionnaire (Supplementary Figure S4) including a ten-point Likert Scale (0 = low, 10 = high). It assessed the subjective exteroceptive acuity for each of the exterosensors: vision, sound, touch, olfaction, taste, and equilibrium.

Control of the nasal functioning has been realized using the DyNaChron (Dysfonctionnement Nasal Chronique) autoquestionnaire. This questionnaire is usually used in the case of chronic nasal dysfunction (Kacha et al., 2012). It assesses the olfactory and gustatory discomfort of the subjects on a daily basis.

The smell test ETOC (European Test of Olfactory Capabilities) [54] was used to assess the olfactory sensitivity of individuals. Individuals must smell the contents of the test tubes (16 sets of 4 test tubes) to find the one containing an odor (discrimination) and the nature of this same odor (identification).

An evaluation of the hedonic value of the detected odor is added. This task was only applied for the subsample of 31 subjects of the cohort.

2.3. Data analsis

Data analyses were performed using Python (Python, Software Foundation, v3.8, Wilmington, DE, USA) and RStudio (RStudio, v1.3.1093, Boston, MA, USA). All scales demonstrated acceptable levels of internal consistency in our sample and subsample (Cronbach's between 0.75 and 0.85). First, a k-means, unsupervised machine learning algorithm using the scikit-learn library in Python, was applied to categorize MD groups according to FMI Presence and Non-judgmental acceptance subscales for all subjects. Second, k-means was applied to categorize MD groups according to FMI Presence and Non-judgmental acceptance subscales only for subjects that complete the ETOC. Due to operational preparations for the mission, not all participants were able to complete the

ETOC. Whatever the sample, the following methodology used is identical. FMI data of participants were previously standardized by removing the mean and scaling to unit variance using the StandardScaler function. Statistical analyses were used to assess the impact of MD clustering on olfactory sensitivity. The Shapiro-Wilk test was used to determine whether data were normally distributed. Homoscedasticity was assessed using the Brown-Forsythe Levene type test. The statistics were adopted following the results of the previous tests. t-test or nonparametric Mann-Whitney analyses were performed individually to explore the presence of significant differences in the olfactory sensitivity according to the MD groups. For all analyses, statistical significance was set at $p < 0.05$. Trends to a difference were considered when $0.05 < p < 0.11$. For significant analyses, the effect size and their confidence intervals (CI) were reported.

Interaction networks (n = 4) were estimated separately for all the subjects and those distributed between both MD groups to explore the connections between mindfulness, interoception, emotions, and subjective exterosensors acuity. Another interaction network was estimated for participants who completed the ETOC using RStudio. A set of variables was considered for all subjects including interoception subscales, mindfulness subscales, positive and negative emotions, and subjective olfactory acuity. For those who completed the ETOC test, the set of variables included interoception and mindfulness subscales, subjective olfactory acuity, and the ETOC performances. Whatever the participants, the methodology used to develop interaction networks is identical. Gaussian graphical models based on partial Pearson correlations were used to evaluate the networks among subjects using the qgraph package [55]. Then, the Least Absolute Shrinkage and Selection Operator (LASSO) regularization method was applied to reduce the likelihood of spurious edges. The Group LASSO (GLASSO) was reported in figures. An Extended Bayesian Information Criterion (EBIC) model was introduced and fixed in the LASSO. Positive edges are shown in green, negative edges are in red, and the relative strength of the edge weight is reflected by edge thickness. Centrality indices were calculated to assess the centrality of the variables related to the strength of its connections with the other variables in the network. The evaluation of the accuracy and stability of the estimated network was determined by bootstrapping using the bootnet package [55]. Nonparametric bootstrap was estimated for edge weights. The stability of strength centrality values was evaluated using the case-dropping subset bootstrap and estimating correlations between the original centrality index and the values obtained from subsets of the data. Plots of edge weight accuracy and stability of strength centrality are in the supplemental materials. Within this network analysis framework estimated for all the subjects and those distributed between both MD profiles, interoception subscales, mindfulness subscales, and subjective olfactory acuity were represented as nodes, and connections between symptoms were undirected edges. Edge weights (strength of connections between two symptoms) correspond to partial correlations that control for all other variables in the network. The overall importance of each variable was evaluated in terms of node centrality strength, which is the sum of absolute values of all edge weights connected to a node. Another interaction network was estimated for participants who completed the ETOC test without clustering using the same method and R packages as before. Within this network analysis framework, interoception subscales, mindfulness subscales, subjective olfactory acuity, and ETOC performances were represented as nodes, and connections between symptoms were undirected edges.

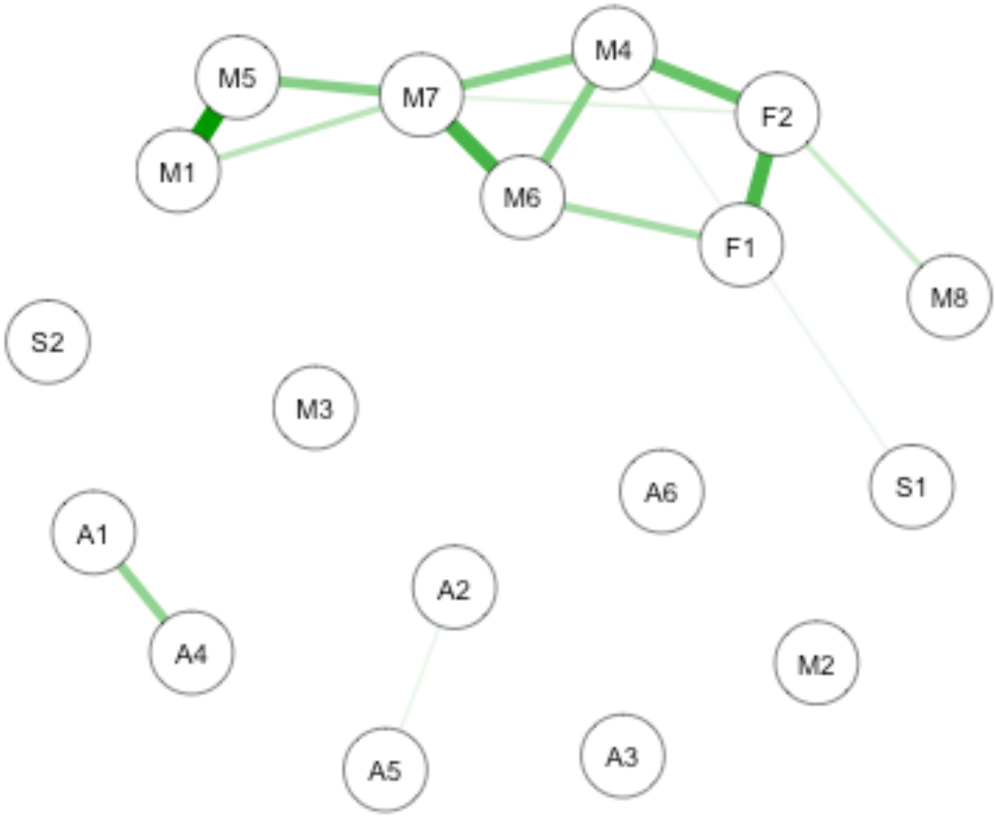
3. Results

Causal interaction network between mindfulness, interoception, emotions, and subjective exterosensors acuity. A causal interaction network was modelized on all the subjects (n = 76) to explore the connections between mindfulness, interoception, emotions, and subjective extrasensors acuity.the connections between mindfulness, interoception, emotions, and subjective extrasensors acuity.

The network is shown in Figure 1.

Figure 1

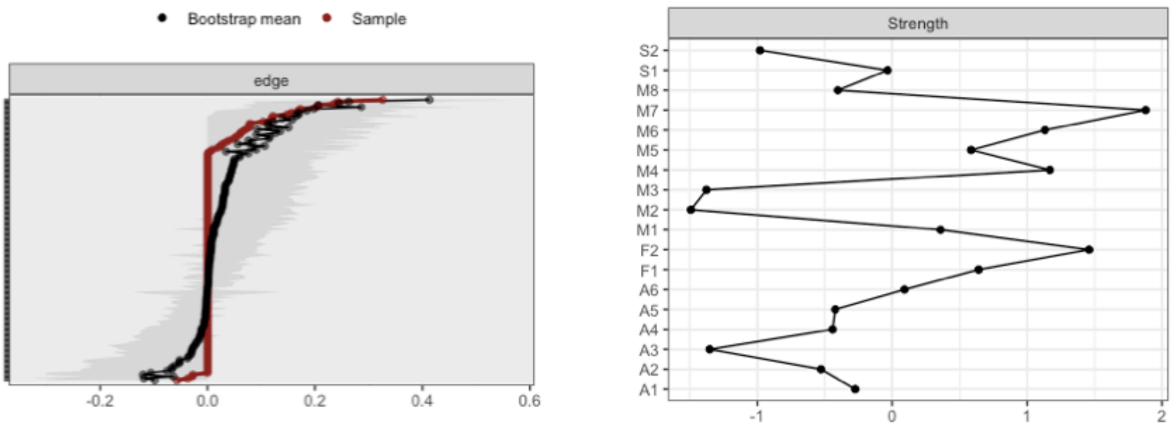
GLASSO-regularized partial Pearson correlation networks of interoception subscales, mindfulness subscales, and subjective olfactory acuity, resulting from all the subjects. Green edges denote positive associations, red edges negative ones. F1: Freiburg Mindfulness Inventory (FMI) presence; F2: FMI Non-judgmental acceptation; S1: Scale of Positive and Negative Experience (SPANE) positive emotion; S2: SPANE negative emotion; M1: Multidimensional Assessment of Interoceptive Awareness questionnaire (MAIA) noticing; M2: MAIA not distracting; M3: MAIA not worrying; M4: attention regulation; M5: MAIA emotional awareness; M6: MAIA self-regulation; M7: MAIA body listening; M8: MAIA trusting; A1: Subjective olfactory acuity; A2: Subjective sight acuity; A3: Subjective hearing acuity; A4: Subjective taste acuity; A5: Subjective equilibrium acuity



The most important connection is between interoception subscales. More precisely, there are notable connections between noticing and emotional awareness. Important connections are also highlighted between self-regulation and body listeninf, noticing and body listening, presence and non-judgmental acceptation, attention regulation, and non-judgmental acceptation. Smaller connections take place between subjective olfactory acuity and subjective taste acuity, presence and self-regulation, attention regulation and self-regulation, trusting and non-judgmental acceptation, attention and body listening, emotional awareness and body listening, and noticing and body listening. Weaker connections are found between subjective sight acuity and subjective equilibrium acuity and positive emotions and attention regulation.

The Correlation Stability (CS) coefficient for edge weights was (*CS*(cor = 0.7) = 0.21), and the CS-coefficient for strength centrality was (*CS*(cor = 0.7) = 0.21), indicating a sufficient level of stability for interpreting rank order of edge weights and strength centrality. Bootstrapping CIs are used to interpret network connections (Figure 2A). The figure reveals sizable bootstrapped CIs around the estimated edge-weights, indicating that many of the edge-weights likely do not significantly differ from one another. The LASSO regularization was also used in the case of partial correlation coefficients for indicating which connections are strong enough to be included in the network.

Figure 2
Estimated edge-weights for the estimated network and centrality nodes. (A) Left: Bootstrapped CIs of estimated edge-weights for the estimated network. The red line indicates the sample values and the gray area the bootstrapped CIs. Each horizontal line represents one edge of the network, ordered from the edge with the highest edge-weight to the edge with the lowest edge-weight. (B) Right: Centrality of nodes within a network for all the subjects

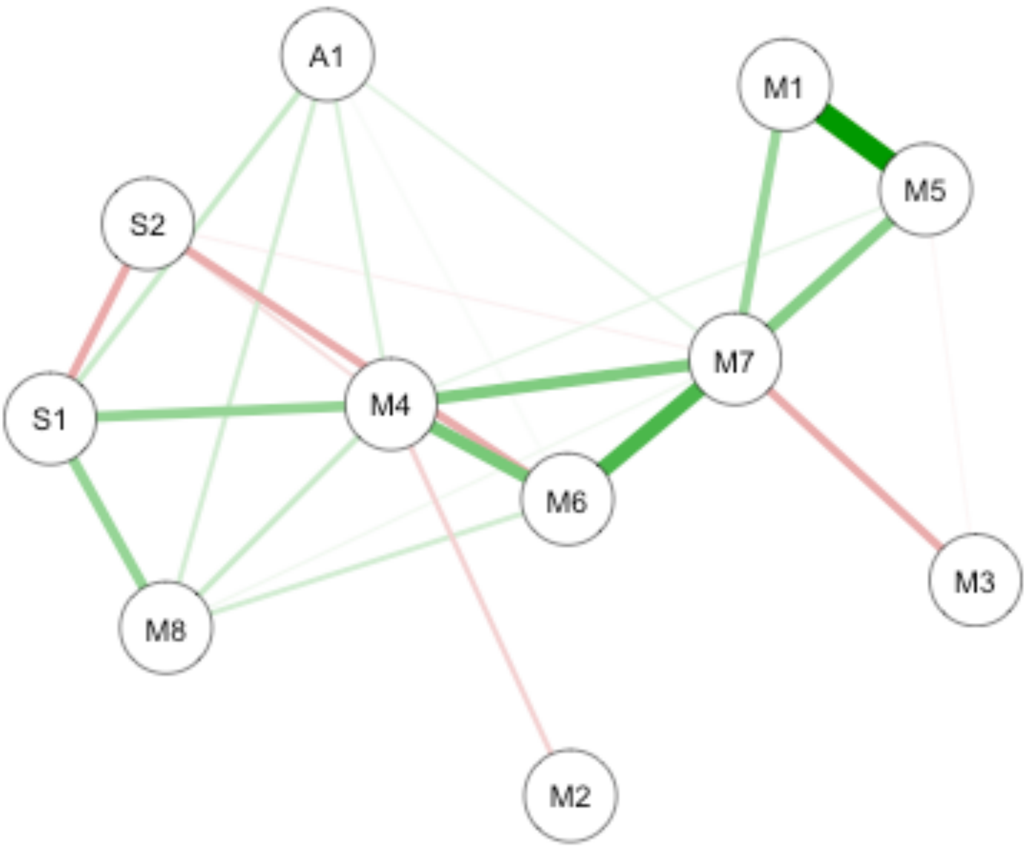


The most central nodes that emerge from the centrality table are linked to interoceptive subscales, including body listening, attention-regulation, self-regulation, and non-judgmental acceptation (Figure 2B). Most notably, body listening was one of the most central variables in the estimated network (Supplementary Figures S5 and S6 for difference tests of node strenght and centralities between all pairs of edge-weight).

3.1. Causal Interaction Network between Interoception, Emotions, and Subjective Olfactory Acuity

A causal interaction network was modelized on all the subjects without group distinction (n = 76) to explore the connections between interoception, emotions, and subjective olfactory acuity. The network is shown in Figure 3.

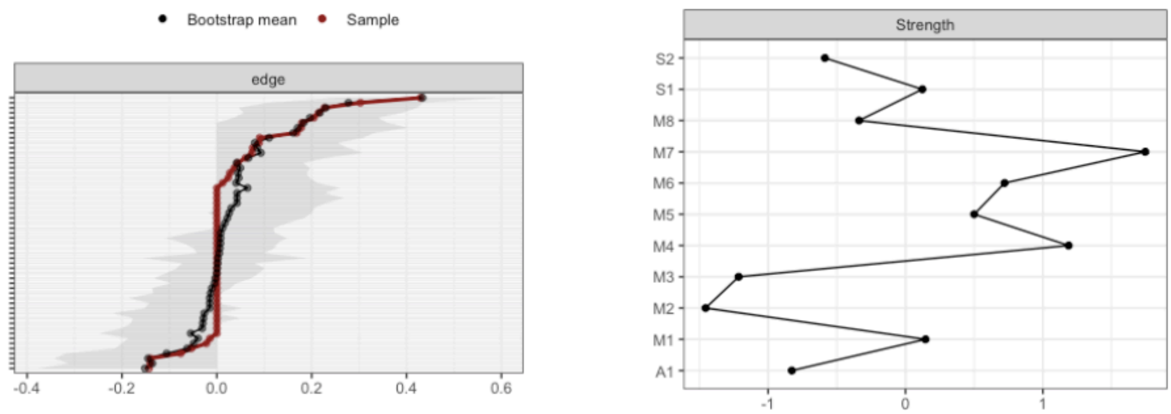
Figure 3
GLASSO-regularized partial Pearson correlation networks of interoception subscales, mindfulness subscales, and subjective olfactory acuity, resulting from all the subjects. Green edges denote positive associations, red edges negative ones. S1: SPANE positive emotion; S2: SPANE negative emotion; F1: FMI presence; F2: FMI non-judgmental acceptation; M1: MAIA noticing; M2: MAIA not distracting; M3: MAIA not worrying; M4: attention regulation; M5: MAIA emotional awareness; M6: MAIA self-regulation; M7: MAIA body listening; M8: MAIA trusting; A1: Subjective olfactory acuity



The most important connection is between interoception subscales. More precisely, there are notable connections between noticing and emotional awareness. Important connections are also highlighted between self-regulation and body listening. Smaller connections take place between noticing and body listening, emotional awareness and body listening, attention regulation and body listening, self-regulation and attention regulation, positive emotions and attention regulation, trusting and positive emotions, negative emotions and positive emotions, not distracting and body listening, and negative emotions and self-regulation. Weaker connections are found between attention regulation and emotional awareness, not distracting and attention regulation, self-regulation and trusting, attention regulation and trusting, subjective olfactory acuity and trusting, positive emotions and subjective olfactory acuity, attention regulation and subjective olfactory acuity, and body listening and subjective olfactory acuity.

The CS-coefficient for edge weights was (*CS*(cor = 0.7) = 0.43), and the CS-coefficient for strength centrality was (*CS*(cor = 0.7) = 0.43), indicating a good level of stability for interpreting rank order of edge weights and strength centrality. Bootstrapping CIs are used to interpret network connections (Figure 4A). The figure reveals linear bootstrapped CIs around the estimated edge-weights, indicating that many of the edge-weights likely significantly differ from one another. The LASSO regularization was also used in the case of partial correlation coefficients for indicating which connections are strong enough to be included in the network.

Figure 4
Estimated edge-weights for the estimated network and centrality nodes. (A) Left: Bootstrapped CIs of estimated edge-weights for the estimated network. The red line indicates the sample values and the gray area the bootstrapped CIs. Each horizontal line represents one edge of the network, ordered from the edge with the highest edge-weight to the edge with the lowest edge-weight. (B) Right: Centrality of nodes within a network for all the subjects



The most central nodes that emerge from the centrality table are linked to interoceptive subscales, including body listening, attention-regulation, emotional awareness, and self-regulation (Figure 4B). Most notably, body listening was one of the most central variables in the estimated network (Supplementary Figures S7 and S8 for difference tests of node strenght and centralities between all pairs of edge-weight).

3.2. Impact of MD Clustering on Psychological Assessments

The k-means characterizes two groups (high vs. low mindful) based on the FMI score of all the participants (Figure 5).

The high mindfulness (n = 32) profile exhibits a higher MD by showing high scores on FMI Presence and Non-judgmental acceptance subscales. The low mindfulness (n = 44) profile exhibits a lower MD by showing lower scores on Presence and Acceptation FMI subscales. A summary of results according to MD profiles on psychological assessments is shown in Table 2.

Figure 5

K-means clustering analysis applied on all subjects based on FMI subscales. Some participants share the same x- and y-coordinates causing them to merge at the same point

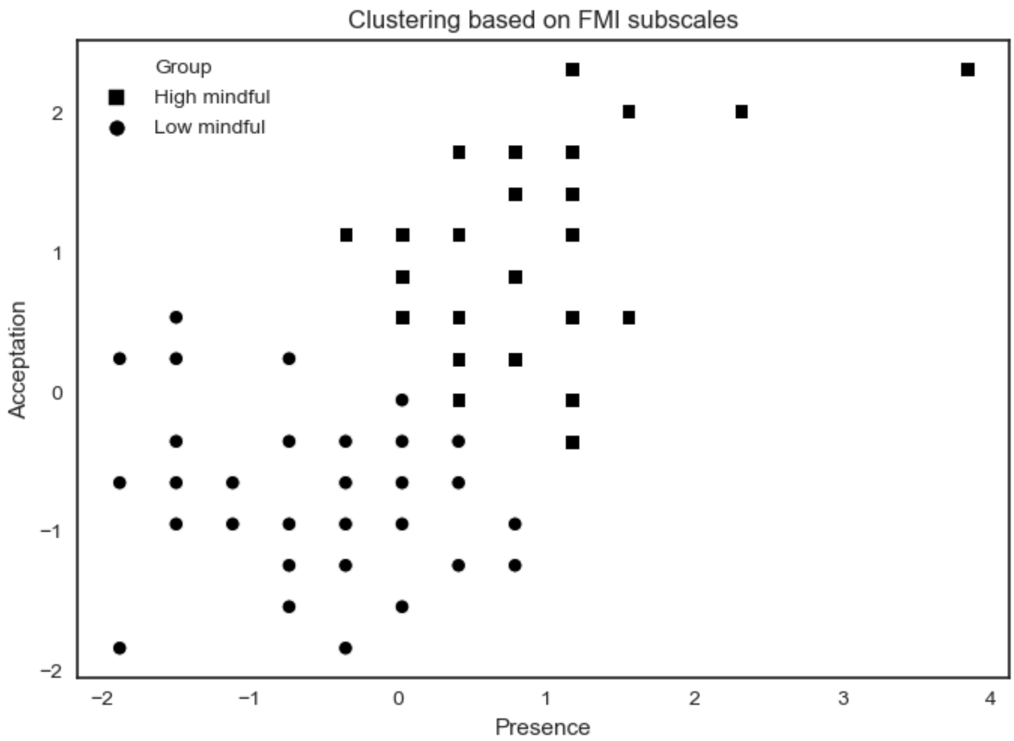


Table 2

Summary of MD profile on psychological assessments (mean ± standard deviation)

Variables	High MD	Low MD	*p*-value*
SPANE Positive	4.22 ± .47	3.94 ± .54	.01
SPANE Negative	2.43 ± .64	2.13 ± .54	.02
MAIA not distracting	2.64 ± .76	2.96 ± .75	.06
MAIA attention regulation	3.37 ± .68	2.51 ± .76	.000
MAIA self-regulation	3.22 ± .79	2.48 ± .84	.000
MAIA body listening	2.66 ± 1.18	1.93 ± .88	.006
MAIA trusting	4.38 ± .59	3.55 ± 1.04	.000
Subjective olfactory acuity	7.69 ± 1.97	6.27 ± 2.40	.008
Subjective taste acuity	8.06 ± 1.79	7.70 ± 2.21	.02
Subjective hearing acuity	8.97 ± 1.12	7.59 ± 2.17	.005
Subjective acuity of balance	8.19 ± 1.45	7.11 ± 2.32	.02
Subjective visual acuity	9.28 ± .92	8.59 ± 1.77	.08

**p*-value for analysis of unit group effect.

In psychological functioning, there is a significant group effect for both SPANE positive (W = 483, p = 0.01, r = 0.27, 95% CI [0.06,0.47]) and negative (t = 2.23, df = 72.49, p = 0.02, d = 0.51, 95% CI [0.04,0.98]) score. The high mindfulness group has higher positive emotions than the low mindfulness group and the opposite for the low mindfulness group.

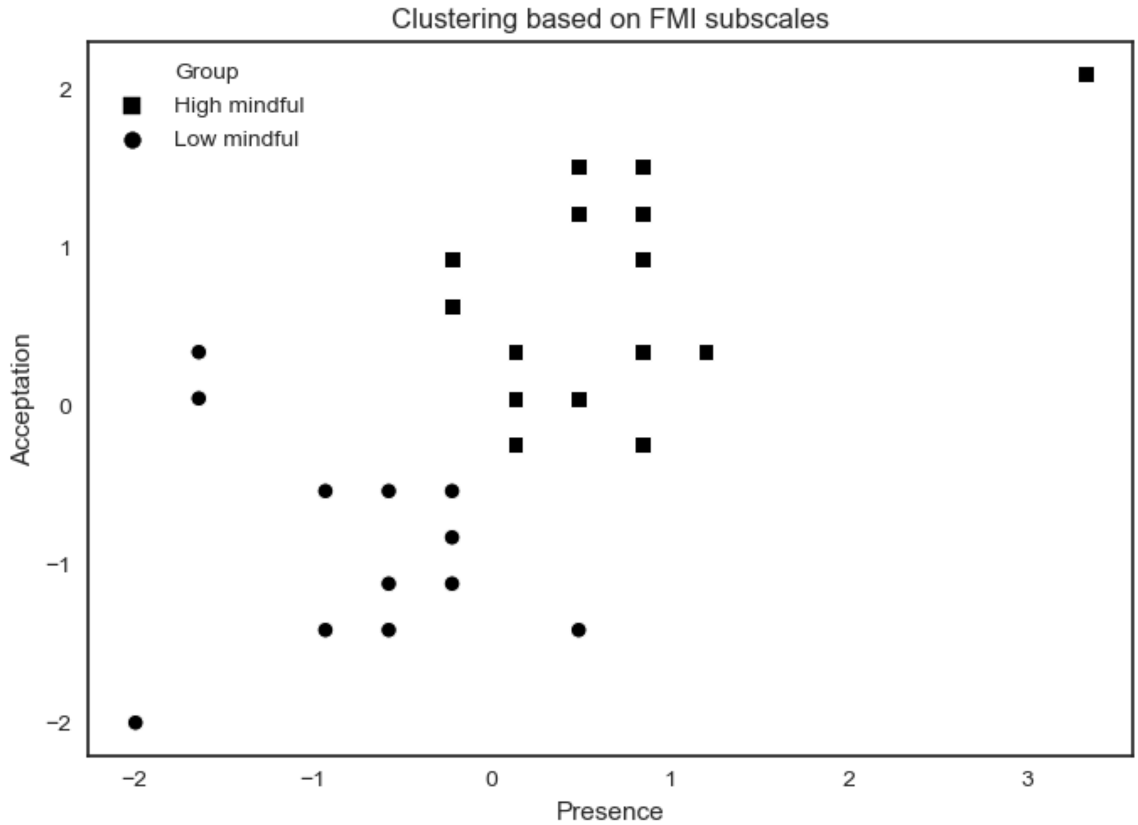
In interoceptive functioning (MAIA), we only found differences for five subscore dimensions. There are significant group effects for attention regulation (t = −5.15, df = 70.58, p = 0.000, d = 1.17, 95% CI [0.68,1.68]), self-regulation (t = −3.88, 68.99, p = 0.000, d = 0.90, 95% CI [0.41,1.38]), body listening (W = 446.5, p = 0.006, r = 0.31, 95% CI [0.09,0.51]), and trusting (W = 349, p = 0.000, r = 0.43, 95% CI [0.22,0.60]). Whatever the dimension, the high mindfulness group has a higher score than the low mindfulness group. There is also a tendency to a group effect (t = 1.84, df = 66.25, p = 0.06, d = 0.43, 95% CI [0.04,0.90]) for not distracting. The low mindfulness group is less distracted than the high mindfulness group.

In subjective exteroceptive acuity, we found differences for each of the exterosensors except for touch. There are significant group effects for olfaction (W = 455, p = 0.008, r = 0.30, 95% CI [0.09,0.49]), taste (W = 500, p = 0.02, r = 0.25, 95% CI [0.05,0.46]), hearing (W = 446, p = 0.005, r = 0.32, 95% CI [0.12,0.51]), and equilibrium (W = 494, p = 0.02, r = 0.26, 95% CI [0.05,0.47]). Whatever the exterosensors, the high mindfulness group has a higher subjective acuity than the low mindfulness group. There is also a tendency to group effect for vision (W = 551, p = 0.08, r = 0.20, 95% CI [0.02,0.41]). The high mindfulness group tends to have higher subjective acuity of vision than the low mindfulness group.

3.3. Impact of MD Clustering on Olfactory Sensitivity Assessments

The k-means characterizes two groups (high vs. low mindful) based on the FMI score of the participants that complete the ETOC (Figure 6).

Figure 6
K-means clustering analysis applied to ETOC performance subjects based on FMI subscales. Some participants share the same x- and y-coordinates, causing them to merge at the same point

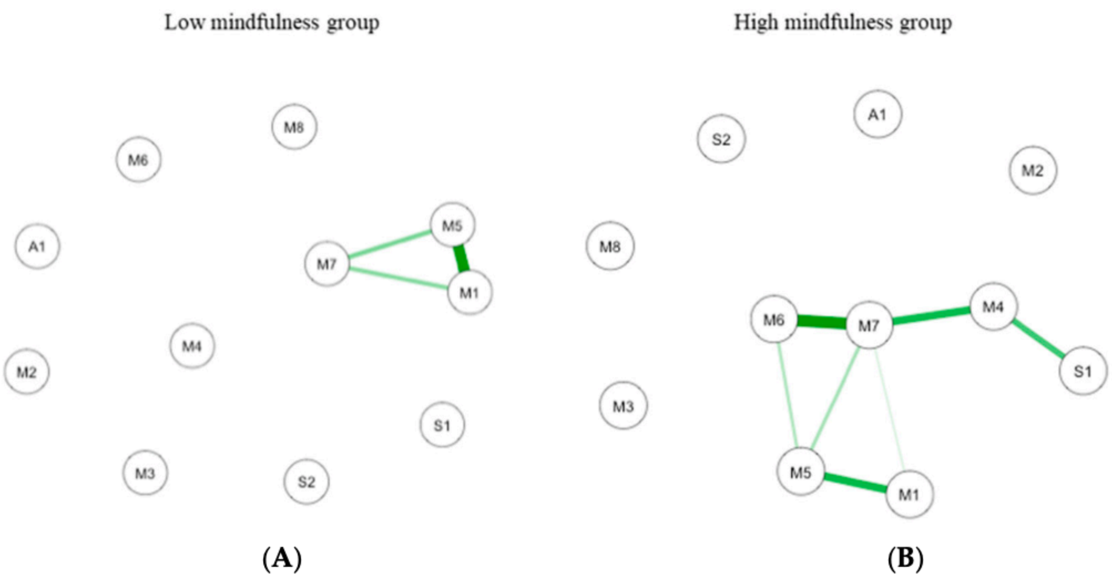


The high mindfulness (n = 18) profile exhibits a higher MD by showing high scores on FMI Presence and Non-judgmental acceptance subscales. The low mindfulness (n = 13) profile exhibits a lower MD by showing lower scores on Presence and Acceptation FMI subscales. A summary of results according to MD profiles on psychological assessments is shown in Table 3.

The dynachron, a test controlling the functionality of the nose, has been assessed and indicated normal values for all study subjects. In olfaction sensory, there is a tendency to a group effect for identification of the odor (W = 77.5, p = 0.106, r = 0.30, 95% CI [0.08,0.61]). The high mindfulness group tends to have a better ability to identify odors than the low mindfulness group. The impact of MD on causal interaction network is shown.

Two causal interaction networks were modelized according to the MD groups (high mindfulness vs. low mindfulness). The network for both MD groups is shown in Figure 7.

Figure 7
GLASSO-regularized partial Pearson correlation networks of interoception subscales, mindfulness subscales, and subjective olfactory acuity, resulting from low mindfulness (A) and high mindfulness groups (B). S1: SPANE positive emotion; S2: SPANE negative emotion; F1: FMI presence; F2: FMI Non-judgmental acceptation; M1: MAIA noticing; M2: MAIA not distracting; M3: MAIA not worrying; M4: MAIA attention regulation; M5: MAIA emotional awareness; M6: MAIA self-regulation; M7: MAIA body listening; M8: MAIA trusting; A1: Subjective olfactory acuity



In low MD (n = 44; Figure 7A), the connections are between interoception subscales. The most important connection is mainly between emotional awareness and noticing. Other connections are between emotional awareness and body listening, and between body listening and noticing. In the high MD (n = 32; Figure 7B the most important connection is between interoception subscales including self-regulation and body listening. Important connections are also highlighted between body listening and auto-regulation, between emotional awareness and noticing, and between autoregulation and positive emotions.

The CS-coefficient for edge weight for low (*CS*(cor = 0.7) = 0.14) and high (*CS*(cor = 0.7) = 0.22) MD networks, and the CS-coefficient for strength centrality weight for low

(*CS*(cor = 0.7) = 0.14) and high (*CS*(cor = 0.7) = 0.28) indicate a sufficient level of stability to evaluate rank order of edge weight and strength centrality.

For the low MD group, bootstrapping Cis are used to interpret network connections (Figure 8A). The CI, estimating the strength of connection, of most interactions is relatively large, suggesting that replication with other samples is necessary to elucidate the strength of these interactions. However, in the case of partial correlation coefficients, the LASSO regularization aims at estimating the connections that do not necessarily have to be exactly zero. Consequently, observing that a connection is not set to zero already indicates that it is strong enough to be included in the network.

The most central nodes that emerge from the centrality table are interoception subscales including emotional awareness, noticing, and body listening for the low MD group (Figure 9A). Most notably, emotional awareness was one of the most central variables, closely followed by noticing in the estimated network (Supplementary Figures S9 and S10 for difference tests of node strenght and centralities between all pairs of edge-weight).

For the high MD group, bootstrapping CIs are used to interpret network connections (Figure 8B). The LASSO regularization was also used in the case of partial correlation coefficients for indicating which connections are strong enough to be included in the network.

The most central nodes that emerge from the centrality table are body listening, self-regulation, emotional awareness, and attention regulation for the high MD group (Figure 9B). Most notably, body listening was one of the most central variables in the estimated network (Supplementary Figures S11 and S12 for difference tests of node strenght and centralities between all pairs of edge-weight).

Figure 8

Estimated edge-weights for the estimated network and centrality nodes. (A) Left: Bootstrapped Cis of estimated edge-weights for the estimated network. The red line indicates the sample values and the gray area the bootstrapped Cis. Each horizontal line represents one edge of the network, ordered from the edge with the highest edge-weight to the edge with the lowest edge-weight. (B) Right: Centrality of nodes within a network for all the subjects

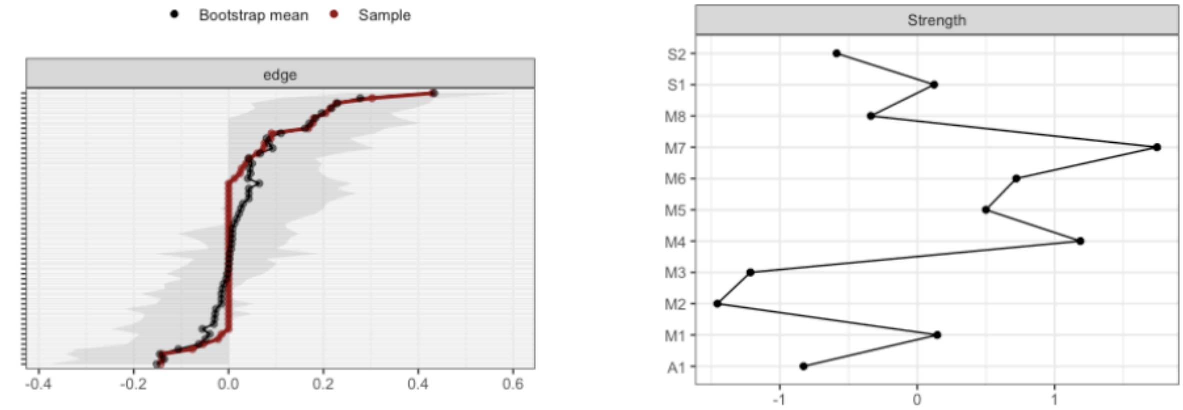
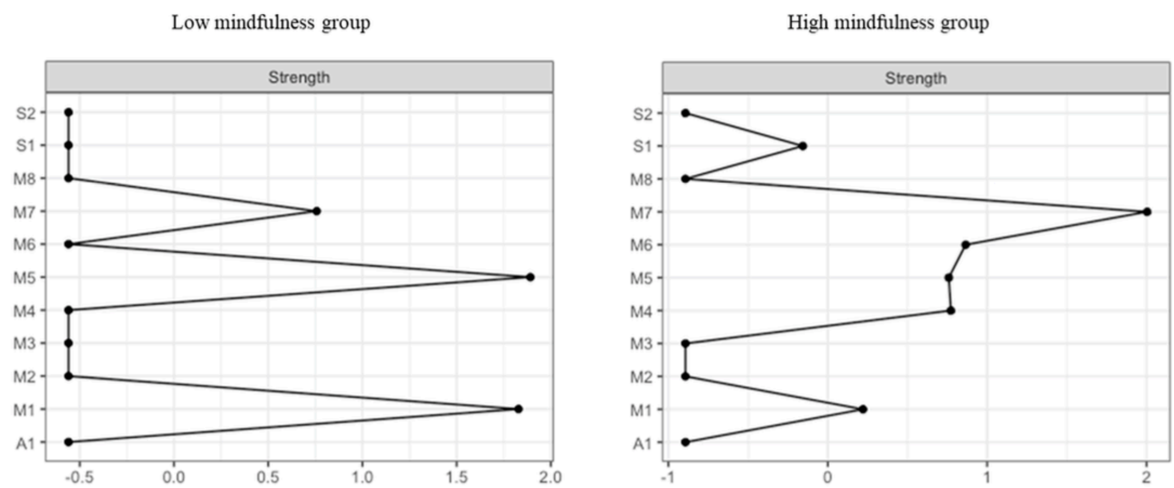


Figure 9

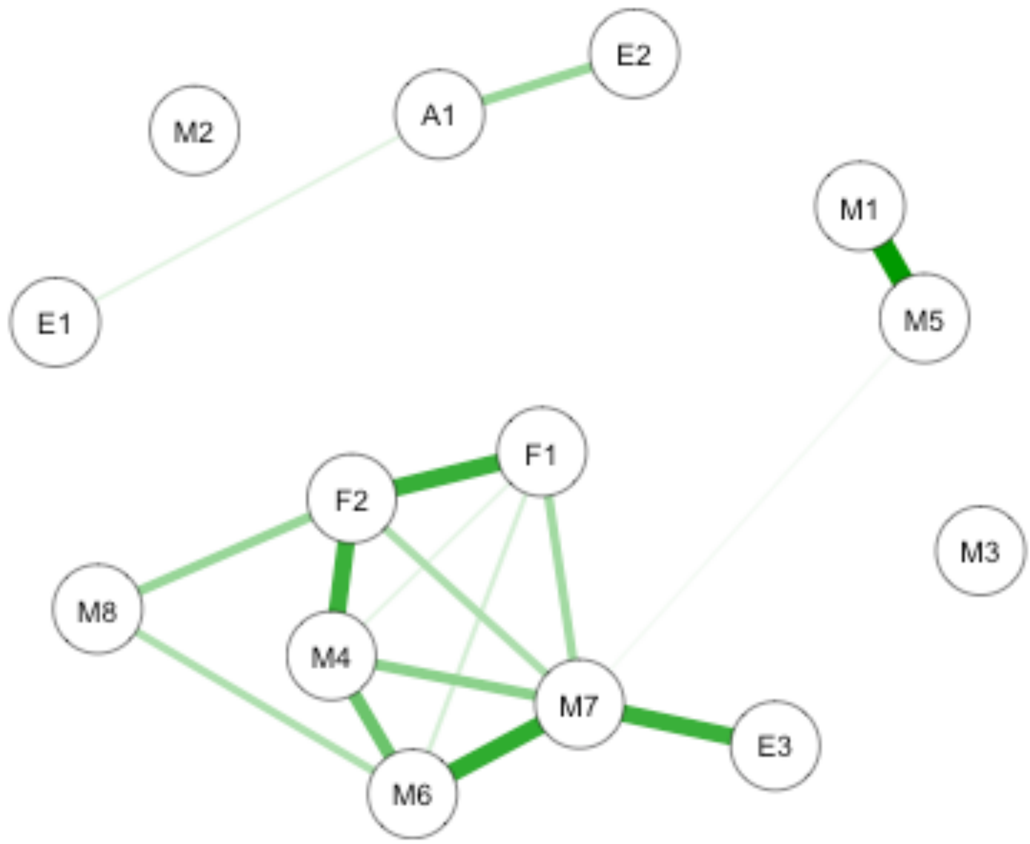
Estimated edge-weights for the estimated network and centrality nodes. Centrality of nodes within a network according to low MD profile (A left) and the high MD profile (B right). S1: SPANE positive emotion; S2: SPANE negative emotion; F1: FMI presence; F2: FMI Non-judgmental acceptation; M1: MAIA noticing; M2: MAIA not distracting; M3: MAIA not worrying; M4: MAIA attention regulation; M5: MAIA emotional awareness; M6: MAIA self-regulation; M7: MAIA body listening; M8: MAIA trusting; A1: Subjective olfactory acuity.



3.4. Causal Interaction Network Using Objective and Subjective Olfaction Data

A causal interaction network was modelized on the subjects who completed the ETOC test (n = 31). The network is shown in Figure 10.

Figure 10
GLASSO-regularized partial Pearson correlation networks of interoception subscales, mindfulness subscales, emotional subscales, subjective olfactory acuity, and ETOC performances. F1: FMI presence; F2: FMI Non-judgmental acceptation; S1: SPANE positive emotion; S2: SPANE negative emotion; M1: MAIA noticing; M2: MAIA not distracting; M3: MAIA not worrying; M4: attention regulation; M5: MAIA emotional awareness; M6: MAIA self-regulation; M7: MAIA body listening; M8: MAIA trusting; A1: Subjective olfactory acuity; E1: ETOC detection; E2: ETOC identification; E3: ETOC hedonic value

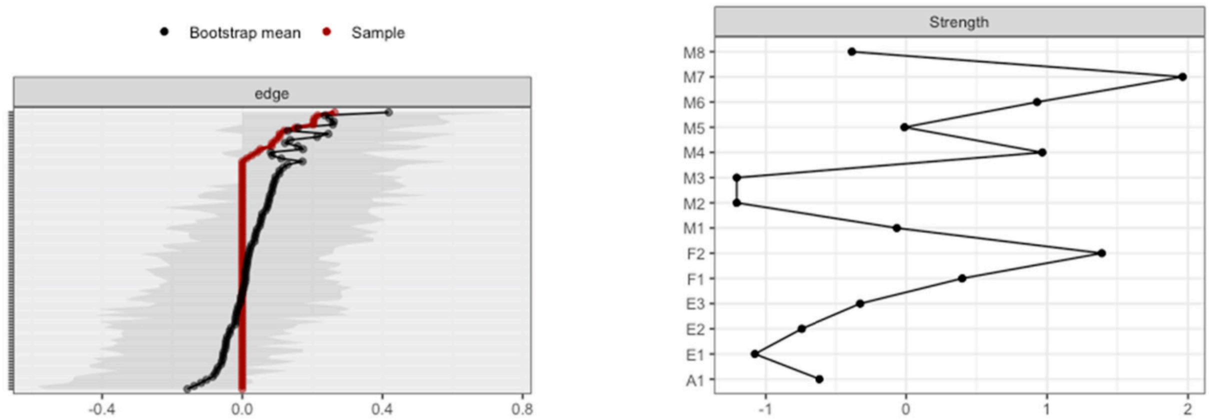


The most important connection is between interoception subscales, FMI Presence, and Non-judgmental acceptance subscales and the ETOC test. More precisely, there are notable connections between noticing and emotional awareness, presence and non-judgmental acceptance, body listening and hedonic value of the ETOC test, body listening and self-regulation, and presence non-judgmental acceptance and attention regulation. Important connections are also highlighted between attention regulation and self-regulation, identification of ETOC odors and subjective olfactory acuity, body listening, and attention regulation. Smaller connections take place between presence and body listening, non-judgmental acceptance and body listening, trusting and non-judgmental acceptance, and self-regulation and trusting. Weaker connections take place between presence and self-regulation, attention regulation and presence, and detection of ETOC odors and subjective olfactory acuity.

The CS-coefficient for edge weights was (CS(cor = 0.7) = 0.07), and the CS-coefficient for strength centrality was (CS(cor = 0.7) = 0.07), indicating a level of stability to be interpreted with caution for interpreting rank order of edge weights and strength centrality. Bootstrapping CIs are used to interpret network connections (Figure 11A). The figure reveals sizable bootstrapped CIs around the estimated edge-weights, indicating that many of the edge-weights likely do not significantly differ from one another. The LASSO regularization was also used in the case of partial correlation coefficients for indicating which connections are strong enough to be included in the network.

The most central nodes that emerge from the centrality table are body listening subscale, non-judgmental acceptance subscale, autoregulation, and self-regulation (Figure 11B). Most notably, body listening was one of the most central variables in the estimated network (Supplementary Figures S13 and S14 for difference tests of node strenght and centralities between all pairs of edge-weight).

Figure 11
Estimated edge-weights for the estimated network and centrality nodes. (A) Left: Bootstrapped CIs of estimated edge-weights for the estimated network. The red line indicates the sample values and the gray area the bootstrapped CIs. Each horizontal line represents one edge of the network, ordered from the edge with the highest edge-weight to the edge with the lowest edge-weight. (B) Right: Centrality of nodes within a network according to ETOC subsample



4. Discussion

The first issue is concerned with the causal interaction network between mindfulness, interoception, exteroception, and emotion. The first hypothesis that reciprocal relationships exist between them is not confirmed. Nevertheless, the first network highlights a causal interaction network between the subscales of interoception, between mindfulness and interoception, between mindfulness and positive emotions, and between subjective olfactory and gustatory acuity. The first causal interaction network clarifies existing results on interoception conceptualized as a multidimensional construct with four key dimensions [3,56]. It shows that the last levels in interoception integration, which is the attentional, the trust, and the mind-body levels, are connected without connection with the first perceived body sensations level. Interestingly, mindfulness level is connected with the three last levels of interoception integration as with subjective olfactory and gustatory acuity. Although these connections between subjective evaluations are small, they are in concordance with prior findings proposing a neurofunctional explanatory model of how olfactory and gustatory exteroceptions trigger the integration of intero- and exteroceptive sensations [36]. Finally, when mindfulness is removed and exteroception reduced to subjective olfactory acuity, results highlight higher connections between the subjective evaluations of the three last levels of interoception, olfactory acuity, and positive emotions. This result asks about the impact of mindfulness level in the observed connections.

The categorical approach aims to evaluate the relationship between MD, interoception, exteroception, and emotion. First, we observed that a high level of MD (i.e., awareness that emerges by paying attention on purpose, in the present moment, and non-judgmentally to the unfolding experience that is moment by moment), as defined by the clustering method, exhibited a more positive emotional state with less negative emotions and more positive emotions. In accordance with the literature on the relationship between mindfulness and emotional functioning [57,58], these results confirm that the two groups are correctly identified and relevant for studying how interoceptive and exteroceptive might interact in the underlying mindfulness mechanisms.

Except for not distracting interoception subscale, the high MD profile was characterized by a higher level of interoception in terms of ability to sustain and control attention to body sensation (attention regulation subscale), to regulate psychological distress by attention to body sensations (self-regulation subscale), to be aware of the connection between body sensations and emotional states (body listening subscale), and to experience one's body as safe and trustworthy (trusting subscale). The high level of not distracting observed for the low MD subjects compared to the high MD subjects might reflect a tendency to ignore oneself from sensations of pain or discomfort that should arrive few weeks before the isolated and confined mission. Interestingly, the high MD subjects exhibited a higher subjective acuity for each of the exterosensors (except the touch) with only a tendency to a difference between the two MD profiles for the vision. The higher subjective acuity for audition, olfaction, and taste for the high MD group is in accordance with both the neurophysiological data highlighting the role of the insula in sensory information integration [36,59] and the better postero- and antero insula functioning after mindfulness training [60]. To date, there is much speculation about insula function in equilibrium, although preclinical evidence exists that the somatosensory and proprioceptive information more strongly activate the posterior insula cortex as compared to the anterior one [61]. In addition, in the subsample of participants with the ETOC performances, the objective evaluation of olfaction tends to differ between both MD profiles only for the identification performances. This lack of results might be due to either a high level of performance in the subsample with very few errors in both olfactory tasks, or a too small size of the sample, or both. Finally, the higher self-report of exteroceptive acuity might indicate that high MD subjects are characterized by either better attention on exteroceptive information, or more confidence in this external information, or a mix of them. The neural exteroceptive processing and its relationship with interoceptive abilities that participate in body awareness must be further studied using neurophysiological investigations for understanding the insula's role as a neural center for the establishment of the psychological construct of the embodied body in humans.

Whether the present results suggest that interoception and olfactory exteroception interact differently according to MD, they need to be completed by the causal network approach. In accordance with our second aim, our main hypothesis is that causal network relationships differ according to the MD profile, with more connections among interoception, olfaction, and emotion for the high MD group only partially validated. What we have here with the causal interaction network approach is that the interoception subscales interactions differed according to the MD profiles. More precisely, we observed an interaction between the interoception subscales for the low MD, contrary to larger connexions in the estimated network for the high MD. For the high MD, there are strong interactions between interoception subscales and positive emotions. These results were supported by the second interaction network that considers all the subjects. The major findings are interactions between interoception and both positive and negative emotions. These results are in line with the interoception to pay attention to body sensation and thus linked to better emotion regulation [58]. Effective emotion regulation involves the ability to evaluate with accuracy the physiological reactions to events. Moreover, the second interaction network highlights evidence for connections between interoception, positive emotions, and subjective olfactory acuity. Soudry et al. [62] in a review claim common brain structures to emotions and olfaction process, olfaction as emotion attributing positive and negative valence to the environment. Among these structures, we note the amygdala, the hippocampus, the insular cortex, and the orbitofrontal cortex. The relationship between the valence of emotion and odor was recently validated by Toet et al. [63] in healthy subjects.

Furthermore, for the sub-cohort, we did not validate the assumptions that mindfulness is most central and has the greatest spreading influence on interoception, olfaction, and emotion. Rather, we found that interoception awareness is strongly connected with both the MD and the hedonic value of odors. These results highlight the centrality of the body-listening subscale, the ability to actively listen the body for insight. We also found this centrality in individuals with a high MD. The interoception awareness seems to have a main role in the MD as well as in the ability to smell odors.

To our knowledge, this is the first study aiming to explore how mindfulness interact with information about the state of the external world (exteroception) and the body's physiological state (interoception) using a causal interaction network. Results first highlight the relevance of the MD characterization for the studies underlying psychological and neurobiological mechanisms involved in mindfulness. Second, they suggest that the fine-tuned interplay between the brain and the body underlies emotional abilities to respond appropriately in a constantly changing environment. It refers to an efficient body awareness that might reflect the individual's ability to feel engaged by information from the body and to notice subtle changes [2]. The differences according to MD might provide arguments for a more mindful attention style toward interoceptive cues in relation to the available exteroceptive information for underlying body awareness abilities. This attention style might be implied in the hedonic value toward exteroceptive information. Thirdly, studying exteroceptive abilities and their changes according to the environmental challenges need further investigation. Especially, olfactory sense might be considered as a singular sense in the ability to cope with adaptation. This question is of interest at least in the field of the isolated and confined environment which exposes the personals to cognitive, psychological, including depressive mood, and sensory disturbances [64,65]. The exceptional nature of these terrains according to the available exteroceptive information means that individuals participating in such missions must experiment and implement several processes to adapt. How exteroception abilities cope with the environmental challenge might be useful for monitoring personals' health. Finally, a better understanding of how the body and the brain interplay may help develop countermeasures to protect workers' health, particularly in situations where they are exposed to high environmental constraints and cognitively demanding situations (e.g., space flights, military operations, etc.).

5. Limitations

The exploratory study has two important shortcomings related to participants and materials. The first one refers to the studied population (i.e., mostly male, young, and selected subjects). The most important limitation is a small size. In these types of environments, it is a huge difficulty to consider due to time constraints, data collected in the ecological environment, and the impact of the environment itself on the psychosensory degradation of these professionals. Effective size is a well-known limitation for causal interaction network studies. Nevertheless, we have considered this limit using bootstrapping. Whether the characteristics of our sample limits a generalization of our results, namely, for women, they offer a very homogenous healthy population. The second one comes from the self-report measures as there are limitations inherent in the self-report approach to assessing any psychological dimensions that include, but are not limited to, response bias, state dependencies, and social desirability. Objective evaluation for exterosensors needs to be developed for healthy subjects with an evaluation of sensitivity for helping researchers to better investigate the role of exteroception in human adaptation. Furthermore, the version of the MAIA developed in 2012 has some problems that are addressed in Mehling et al. [56]. The new version of the MAIA (MAIA-2) includes a much broader awareness focus on thoughts and exteroceptive stimuli. This new scale might be more informative for our question.

6. Conclusion

This exploratory study explores how mindfulness interact with information about the state of the external world (exteroception) and the body's physiological state (interoception) using interaction networks. First, results highlight interactions between mindfulness, interoception, emotions, and subjective olfactory acuity, underlying common brain structures in the literature. Secondly, they claim the relevance of the MD characterization for the studies underlying psychological and neurobiological mechanisms involved in mindfulness. Thirdly, they suggest that the fine-tuned interplay between the brain and the body underlies emotional abilities to respond appropriately in a constantly changing environment. Further investigation is needed to study exteroceptive abilities and their modifications function of the environmental challenges. A better understanding of how the body and the brain interplay may help develop countermeasures to protect workers' health, particularly in situations where they are exposed to high environmental constraints and cognitively demanding situations (e.g., space flights, military operations, etc.).

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8. Supplementary Material

The following are available online at https://www.mdpi.com/2076-3425/10/12/921/s1, Figure S1: FMI; Figure S2: MAIA; Figure S3: SPANE; Figure S4: Subjective acuity; Figure S5: Bootstrapped difference test (α = 0.05) according to all variables of all participants between the weight of non-zero connections in the causal network. Grey boxes indicate connections that do not differ significantly from each other. Black boxes indicate significant interactions; Figure S6: Boostrapping difference test (α = 0.05) according to all the variables of all participants between non-zero node forces in the causal network according to the high MD group. Grey boxes indicate connections that do not differ significantly from each other. The higher the number, the more central the corresponding node is. Black boxes indicate significant interactions; Figure S7: Bootstrapped difference test (α = 0.05) according to all participants sample between the weight of non-zero connections in the causal network. Grey boxes indicate connections that do not differ significantly from each other. Significant interactions are reported in black boxes; Figure S8: Boostrapping difference test (α = 0.05) according to all participants sample between non-zero node forces in the causal network according to the high MD group. Grey boxes indicate connections that do not differ significantly from each other. The higher the number, the more central the corresponding node is. Black boxes indicate significant interactions; Figure S9: Bootstrapped difference test (α = 0.05) according to the low MD group between the weight of non-zero connections in the causal network. Grey boxes indicate connections that do not differ significantly from each other. No significant interaction is reported; Figure S10: Boostrapping difference test (α = 0.05) between non-zero node forces in the causal network according to the low MD group. Grey boxes indicate connections that do not differ significantly from each other. The higher the number, the more central the corresponding node is. No significant interaction is reported; Figure S11: Bootstrapped difference test (α = 0.05) according to the high MD group between the weight of non-zero connections in the causal network. Grey boxes indicate connections that do not differ significantly from each other. No significant interaction is reported; Figure S12: Boostrapping difference test (α = 0.05) between non-zero node forces in the causal network according to the high MD group. Grey boxes indicate connections that do not differ significantly from each other. The higher the number, the more central the corresponding node is. No significant interaction is reported; Figure S13: Bootstrapped difference test (α = 0.05) according to sub-sample who completed the ETOC between the weight of non-zero connections in the causal network. Grey boxes indicate connections that do not differ significantly from each other. No significant interaction is reported; Figure S14: Boostrapping difference test (α = 0.05) according to sub-sample who completed the ETOC between non-zero node forces in the causal network according to the high MD group. Grey boxes indicate connections that do not differ significantly from each other. The higher the number, the more central the corresponding node is. No significant interaction is reported.

Synthèse des résultats principaux

L'étude NEURAL NETWORKS avait trois objectifs principaux : (1) établir un réseau d'interactions causales entre les variables d'intéroception, d'olfaction, de MD et d'émotions ; (2) investiguer si la MD est associée avec un haut niveau d'intéro-extéroception et émotionnel ; et (3) évaluer comment la MD interagit avec les autres variables susmentionnées en employant un réseau d'interactions causales.

L'approche des réseaux d'interaction causale révèle une connexion importante entre la MD et les voies intéro- et extéroceptives. Cette approche statistique présente l'intérêt de mettre en évidence des dépendances causales entre des variables participant à une même fonction, ici l'adaptation. Une fois que la structure du réseau est estimée, la visualisation du graphique nous permet d'avoir une idée précise des dépendances entres les variables. De plus, des méthodes d'estimation statistique peuvent être utilisées de manière à faire ressortir le nœud le plus important du réseau, qui sera le plus central au sein de la structure. Cette approche montre un fonctionnement intéroceptif différent selon les profils de MD. Les résultats mettent également en évidence qu'un haut niveau de MD est associé à une meilleure intéroception et une acuité sensorielle subjective plus élevée ainsi qu'à des émotions positives plus importantes. Cette étude souligne ainsi l'implication des relations intéro- et extéroceptives et de la qualité de la présence à ces informations d'un état émotionnel positif. Ces relations pourraient participer à rendre compte de l'impact d'une haute MD sur l'adaptation et au-delà sur la santé.

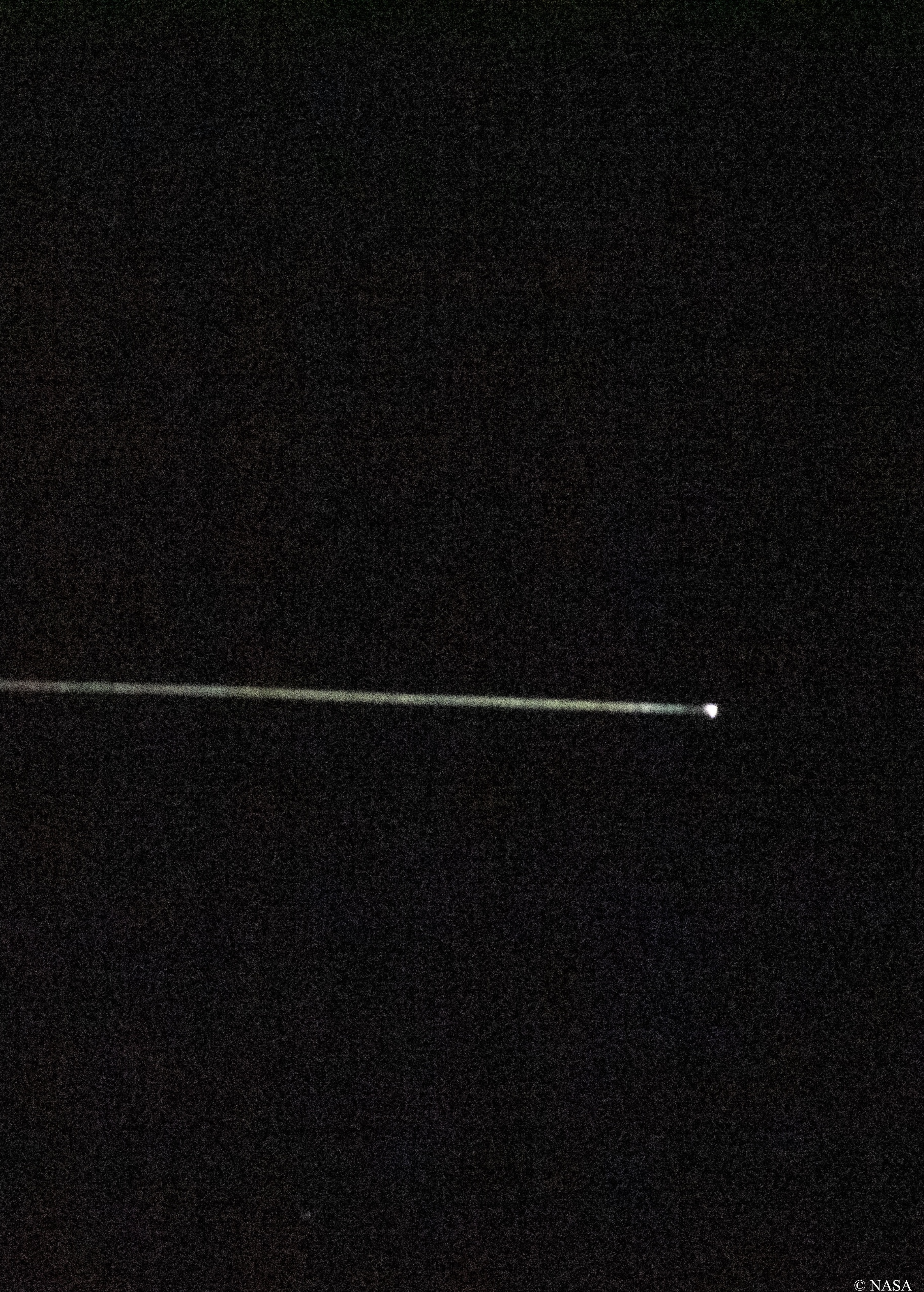
Un deuxième travail de validation du cadre d'étude de l'adaptation en environnement contraint a été réalisé afin de proposer un modèle à partir des données recueillies dans certaines études de la partie expérimentale présentée dans le chapitre II. Il s'agit de valider un ensemble de processus de régulation physiologiques et comportementaux qui permettent à l'organisme de se maintenir dans son état d'homéostasie afin de répondre aux changements environnementaux dans la durée. Tandis que l'homéostasie sous-tend que l'organisme maintienne son milieu intérieur à un état d'équilibre constant, l'allostasie prend en compte sa variabilité. L'homéostasie et l'allostasie permettent ainsi au cerveau de fonctionner de façon efficiente en reposant sur une intégration multimodale des processus de régulation des informations intéro- et extéroceptives.

Berntson et al. (2019) explorent le lien entre intéroception et ANS. Pinna et Edwards (2020) proposent un modèle de maintien de l'adaptation, notamment émotionnelle, basé sur la qualité de l'interaction entre l'intéroception et l'ANS. Les individus ayant une interoception de qualité et une réponse autonome ajustée à la demande de l'environnement seraient plus à l'écoute des modifications physiologiques qui s'opèrent lors de l'exposition à une situation stressante. Ils auraient ainsi des capacités d'adaptation plus importantes. Ces biomarqueurs pourraient ainsi être pertinents pour gérer les stresseurs à court et long terme, quel que soit leur intensité et permettre une meilleure récupération.

Pour autant, ce modèle demande à être évalué dans les environnements singuliers que représentent les missions ICE/EUE. D'un point de vue différentielle, il offre également un cadre pour valider si les biomarqueurs intéroceptifs et l'ANS, notamment vagal permettent de déterminer pour quelle raison certains individus réagissent plus fortement ou à l'inverse pour quelle raison certains semblent protégés face à des stresseurs identiques.

L'étude AI (intelligence artificielle, *artificial intelligence* en anglais) avait deux objectifs principaux : (1) identifier des profils d'adaptation chez les professionnels en environnement ICE/EUE, en utilisant les informations intéroceptives, physiologiques avant le départ en mission ; (2) appliquer les outils de l'AI pour évaluer leur apport dans des situations de terrain présentant des contraintes proches bien que différentes.

Nous posons l'hypothèse qu'un fonctionnement parasympathique élevé, et de plus grandes capacités intéroceptives sont associés à une meilleure adaptation au cours de la mission ; et qu'ils permettent de discriminer une population qui présente une variabilité inter-individuelle importante.



We Have Liftoff: Identification of Adaptation Profiles and Challenges for Future Space Missions

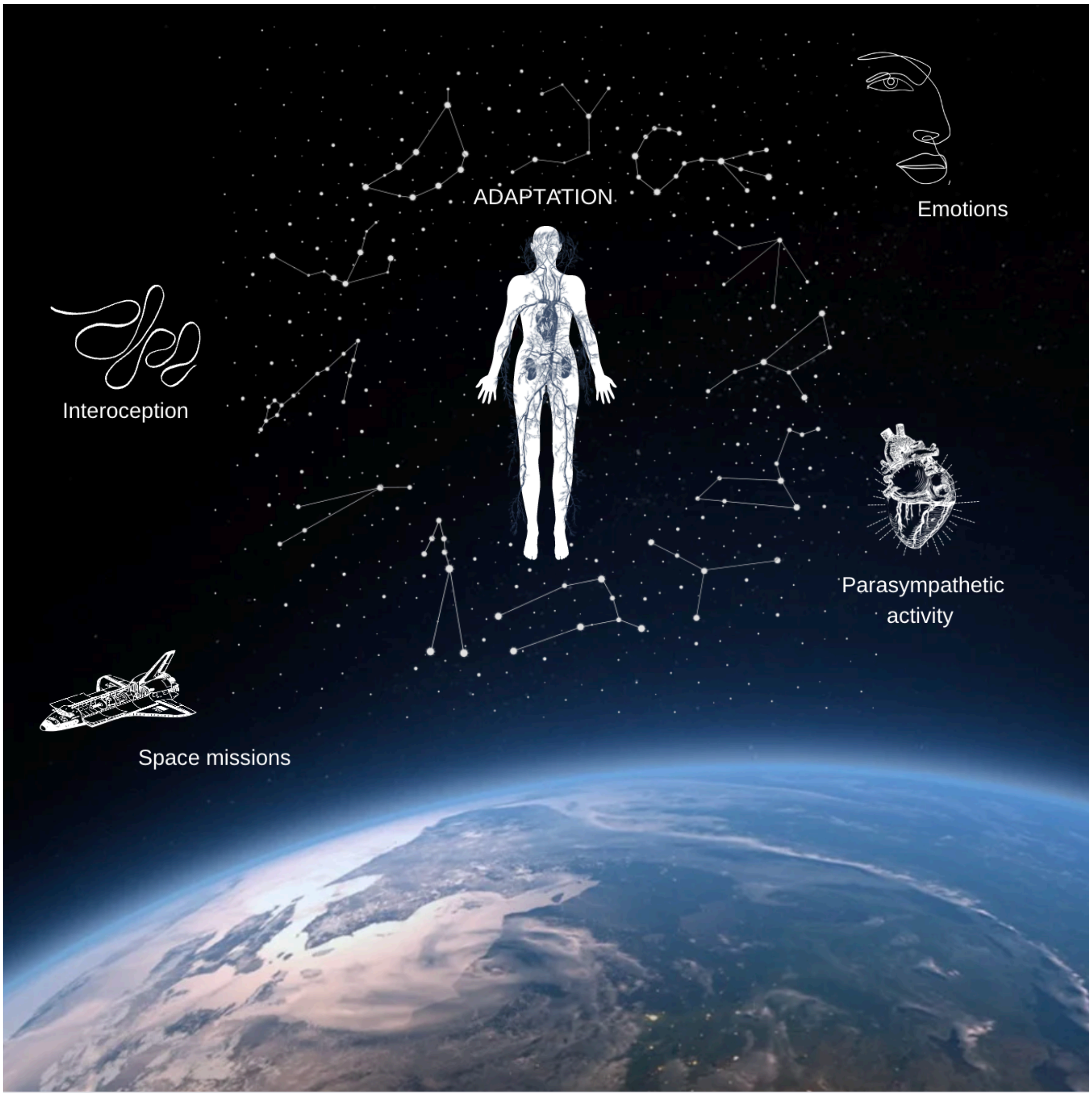
Soumis[13]

[13] Le Roy, B., Claverie, D., Sauvadet, L., Martin-Krumm, C., & Trousselard, M. (2023). We Have Liftoff : Identification of Adaptation Profiles and Challenges for Future Space Missions. *PLoS ONE*.

Abstract

Literature on space and space analogs have highlighted both pathogenic and salutogenic impacts on health. The human challenge of future long space missions will be to maintain the adaptative capacities of astronauts during the mission. Interoception and heart rate variability (HRV) have been found to participate to health outcomes by predicting adaptation to and adaptability. They participate to a safe or an unsafe neuroception. However, few research has evaluated their interests in space and analogs. The objective of this study is to predict adaptation profiles based on interoceptive, and HRV (i.e., linked to parasympathetic activity) data in space analogs characterized by confined and/or isolated and/or extreme and/or unusual condition. 84 participants across fixe space analogs environment (i.e., parabolic flights, nuclear sub-surface submarine, simulation of survival at sea, CBRN protective equipment) constituted the dataset. Interoceptive sensitivity, as well as HRV were recorded at baseline and post mission for calculating measures evolutions to define profiles of adaptation using clustering analysis. Baseline interoceptive and HRV data were then used in a support vector machine (SVM) learning model algorithm to predict these adaptative profiles. Results reveal three adaptative profiles. The first one exhibits an alteration of interoceptive awareness. The second one exhibits a disconnection of interoceptive awareness with an increase confidence in attention to low-level perceptual interoceptive changes but a decrease interoceptive body-mind integration. Both the first and the second profile, no conclusive findings on neuroception response can be made as they have extreme inter-individual variability. The third profile also exhibits a disconnection between deteriorating interoceptive perception and increasing body-mind integration. Compared to the two previous profiles, this one appears to mostly impair neuroception. These three profiles could be predicted form baseline by the mean of a SVM classifier yielded to 79% accuracy. This preliminary work demonstrates that it is possible to identify constraints situations using machine learning, that the mind-body nature of adaptation and the implication of different levels of interoceptive pathways towards HRV responses. It is relevant for better adapt how to train professional adaptation to space missions and to analogs before missions. They raise the importance to study adaptation in space analogs to provide efficient countermeasures during the mission. As tomorrow is no longer waiting, we are take-off.

Figure 23
Graphical abstract



Keywords

Adaptation, Classification, Health, Machine learning, Space analogs

1. Introduction

With the upcoming long duration space exploration (LDSE) programs, it is essential to ensure that the risk to astronaut crews is substantially limited. The literature on space and space analog environments has highlighted a psychiatric, psychological, cognitive, physiological, neurophysiological, sensory, and post-mission impact that is both pathogenic and salutogenic, non-linear over time, and the need for countermeasures to improve adaptation [1]. Living is space will therefore constitute a challenging endeavour. *Adaptation* or the ability of a person to change or adjust in response to changing conditions or situations [2] is one of the five components identified by NASA for future long-distance space travel [3]. Some individuals will adopt several adaptive strategies, in many cases specific to each one of them [1]. All these reactions contribute to the achievement of a state of balance in response to the new environmental constraint. Research into preventive and anticipatory countermeasures is fundamental to ensuring health under stress. They act before the emergence of pathology, to prevent its occurrence, delay or limit its effects. In the case of LDSE, the concern is not to annihilate the emergence of a disease, but to ensure appropriate, early-phase allow to support an adaptive human response. So, the challenge is also to understand the mechanisms by which individual's resources are no longer sufficient to ensure his or her adaptation to the environment, or alternatively, why certain individuals maintain their adaptive capacities when confronted with the same level of stressors. Consequently, when exposed to stressful situations, a set of physiological and behavioral regulatory loops are activated to respond to environmental changes. While homeostasis implies that the organism maintains its internal environment in a constant state of balance, allostasis considers its variability [4, 5]. We refer to allostasis to describe the stability of the organism through change, through regulatory mechanisms that ensure the independence of the internal environment from the external environment [6].

Whether interest of human adaptability to space environments and space analogs is a key topic, mind-body adaptation and flowing stresses by itself is the most important aspect of human adaptability in the recent literature. Studies have shown that the stress response causes an alteration in central nervous system (CNS) signals. The stress response is regulated by two main systems: autonomous nervous system (ANS) and the hypothalamic-pituitary-adrenocortical (HPA) axis. Both these systems are activated faced to a stressor and mediate allostatic processes necessary to allow survival [7, 8]. Nevertheless, long-term exposure to stressors may dysregulate physiological stress axes. Some evidence suggests that the ability to emotionally regulate successfully may be strongly dependent on the moment-to-moment awareness of bodily parameters relayed via interoceptive pathways [9, 10]. Interoceptive pathways participate to the stress response due to the permanent bidirectional communication along the brain-body axis and through activation of several brain structures (e.g., nucleus tractus solitarius, thalamus, anterior cingulate cortex, insula) [11]. Interoception refers to the process by which the CNS senses, interprets, integrates, regulates signals originating from inner state of the body, 'providing a moment-by-moment mapping of the body's internal landscape across conscious and unconscious levels' [12, p.1]. Therefore, interoception provides information on the internal physiological state [13, 14]. Sensory information is transmitted to the CNS through two pathways: the lamina I pathway and the vagus nerve, depending on whether the innervation falls under the sympathetic nervous system (SNS) of the ANS (i.e., type Aδ and type C fibers carry sensory afferents to lamina I, then project to the superior part of the ventromedial nucleus) or the parasympathetic nervous system (PNS, i.e., sensory afferents project to the parabrachial nucleus and nucleus of the solitary tract, then to the basal part of the ventromedial nucleus of the thalamus) [13]. Interoceptive awareness refers to the inclination to pay attention to one's bodily sensations, and this subjective trait is assessed using self-report measures. In their process of developing the original scale examining body awareness (Multidimensional Assessment of Interoceptive Awareness, MAIA), Mehling et al. [15, 16] distinguished four levels of body awareness: a first, perceptual and sensory level involves the perception of sensations and the ability to discern bodily cues testifying to the physiological and emotional state of the body; in a second stage, attention is directed towards the SCs and the attentional response is coupled with an emotional evaluation; at the next level, the attitude of interoceptive awareness corresponds to beliefs relating to bodily sensations; finally, the body-mind integration corresponding to body awareness is located at the last level. Individuals with a high level of interoception, as assessed by the MAIA, would more efficiently manage acute stressful situations [17, 18], and would have positive outcomes on health (Khalsa et al., 2018). Interoception therefore ensures homeostatic and allostatic adaptations of the body via improved self-regulation of information [18]. The interoceptive system could be responsible for creating homeostatic maps of the body that serves to orchestrate regulatory responses over time [19]. The regulatory responses would act both at a conscious level, through emotions and feelings, and at the autonomic level [19].

This concept is in line with the notion of neuroception, which involves the neural process by which the degree of safety or threat contained in the environment is assessed [20]. According to the polyvagal theory, the ANS has evolved to respond to different levels of threat. Therefore, the vagus nerve may be viewed as a constant brake and released when the SNS is activated leading to different adaptative behaviors [21]. Kashdan and Rottenberg [22] argue that the vagus nerve serves as an indicator of psychological flexibility, which is essential for psychological health. More recently, the genomics, environment, vagus nerve, social interaction, allostatic regulation, and longevity model (GENIAL) developed by Mead and collaborators [23] appears to capture the evolution toward pathology occur and promote health and longevity. One of the regulators is the vagus nerve, indexed by the Heart Rate Variability (HRV). HRV has been considered as a marker of adaptation and an efficient indicator of health [24]. More specifically, HRV is an index of the cardiac frequency evolution. Higher parasympathetic level in HRV is associated with better greater executive function, stress management, and social engagement [25]. It is indicative of increased adaptative abilities [1, 10, 20, 24], and health outcomes [26–28]. In a review, Pina and collaborators [29] highlighted that HRV, especially the parasympathetic branch of the ANS, and interoception leads to increased emotional regulation, especially the parasympathetic activity has been associated with better adaptative emotional regulation strategies. Other studies found that interoceptive processing is also engaged in emotional processing [30, 31].

Although crews will be trained and prepared, they are not superhumans. They may have the resources to cope with most hazards, but what they will encounter is beyond prediction. No place on Earth is sufficiently extreme to replicate all the stressors of an LDSE mission. The main stressors are characterized by isolated and confined environments (ICE) that can be combined with extreme and unusual environments (EUE). Such environmental constraints are experimented in space analogs [1]. They are known to provide unique opportunities to study human adaptation in ecological environments, where the risk of life-threatening is everywhere. The most common environments used as space analogs are polar stations, space simulations facilities, as well as sub-surface ballistic nuclear-powered missile submarine (SSBN). They shared similar environmental stressors and mission requirements (e.g., selection procedures, crew composition, high-technological facilities, mission's profile, skills). Whether data on analogs based on professional or experimental subjects are not similar to data from astronauts during space mission, nevertheless, they provide an opportunity to expose crews to some of these stressors for a specific period of time, and thus to approximate to the ecological environment with strong analogies with space environments.

Furthermore, literature, especially reviews provide a rich framework including psychobiophysiological and social relevant variables as key factors implied in space adaptation. Nevertheless, classical statistics are the most common reference. The emergence of artificial intelligence (AI) may offer a way of better understanding and predicting which individuals are most at risk of deteriorating during a mission in these unusual environments. AI is at the forefront of medicine, where real-time monitoring feeds the algorithm's database. More specifically, machine learning provides new way of thinking to understand human behavior. Furthermore, they allow the ability to mine structured knowledge from extensive data. They appear to be predisposed to address many challenges in the upcoming era of precision space medicine, especially in terms of predictive profiles of subjects for a complementary understanding of adaptation and for adjusted training and countermeasures.

The general objective of this pilot study is to study the contribution of machine learning analyses to better understand the interoceptive and HRV factors predicting the adaptation to a mission in space analogs. It is based on several studies that have explored the changes in interoceptive and parasympathetic autonomic level in healthy subjects that have experimented missions in ICE and/or EUE space analogs (dataset). It aims exploring the question of adaptation to space analogs using machine learning techniques that will be applied to find a model, if any, which could account for the adaptative responses from the interoceptive and parasympathetic autonomic variables (features). More precisely, in a first step, this study aims to define profiles of adaptation based on mind-body changes between before and after the mission. In a second step, it focuses to predict the profiles of adaptation using the mind-body functioning before the mission.

2. Method

2.1. Participants and Data Collection

The dataset contains 114 subjects and 42 variables. Once we have decided which missions to keep for our study, 16 variables and 84 participants were included in the remaining dataset. We have used a combination of data from four experimentations conducted in space analogs: (1) parabolic flights in microgravity (ENACT) characterized by EUE constraints, (2) mission in a a SSBN characterized by 2-months ICE constraints and two simulated crisis ICE/EUE situations. The first one is a simulation of survival at sea (RAD'LÔ), and the second one is a simulation of medical intervention under CBRN attack with protective equipment that could be compared to an astronaut's extravehicular suit (ANTIDOTE). Therefore, the dataset involved 17 healthy scientifics including researchers (n = 7), physicians (n = 5), academic coordinators (n = 3), engineers (n = 2), and other (n = 1) ; 19 male submariners belonging to the crew of the SSBN Le Triomphant ; 21 healthy marines from the French Maritime Academy (n = 15), firefighters from the Marseille Naval Fire Battalion (n = 2), and volunteers from the Camondo Design School (n = 4) ; 27 healthy firefighters from the BSPP. The features and their description are described in Table 1.

Table 1

Socio-demographic characteristics of participants

Measurements	ENACT*	SSBN*	RAD'LÔ*	ANTIDOTE*
N	17	19	21	27
Mage	41.35 ± 8.95	29.73 ± 6.94	22 ± 6.3	31.90 ± 7.0
Mheight	177.35 ± 6.83	NA	178 ± 9.41	175.00 ± .00
Mweight	69.71 ± 9.06	75.78 ± 8.77	71.1 ± 13	75.51 ± 13.85
Gender (women/men)	23.52% - 76.47%	0% - 100%	33.33% - 66.66%	22.22% - 77.77%
In couple/with children	100% - 52.94%	78.94% - NA	38.09% - 9.52%	88.88% - 37.03%
Contraception	25.00%	NA	28.57%	14.81%
Clinical medical history (i.e., hip replacement, deafness, pneumothorax)	11.76%	NA	4.76%	4.76%
Right-handed/left-handed	NA	100% - 0%	80.95% - 19.04%	NA
Personal major stressful events	2.66 ± 1.37	8.00 ± .50	NA	1.5 ± .83
Professional major stressful events	6.00 ± 5.04	5.00 ± .45	NA	2.33 ± 1.21
Previous experience in extremes	35.29%	100%	NA	NA

*Mean and standard deviation are reported when necessary. Other figures show the ratio of the number of subjects. NA indicates a naan value.

Table 2 presents the characteristics of stress stressors in space analogs.

Table 2

Characteristics stressors in space analogs

Stressors	ENACT*	SSBN*	RAD'LÔ*	ANTIDOTE*
Extreme	-	High	Very high	-
Unusual	-	High	Very high	High
Isolation	-	~80 days	5 days	~2 heures
Confinement	~4 hours	~80 days	-	~2 heures
Length	~4 hours	~80 days	5 days	~4 heures
Ecology	Real	Real working environment	Real training	Simulation training
Stress	Acute	Chronic	Acute	Chronic
Sensory stimuli	High	Very low	Very high	Low
Threat	Low high	High	High	Low
Communication	Good	Complex	Complex	Complex

*ENACT = parabolic flights in microgravity; SSBN = sub-surface ballistic nuclear-powered missile; RAD'LÔ = simulation of survival at sea; ANTIDOTE = simulation of medical intervention under CBRN attack with protective equipment.

2.2. Variables & Measurements

2.2.1. Psychological measurements

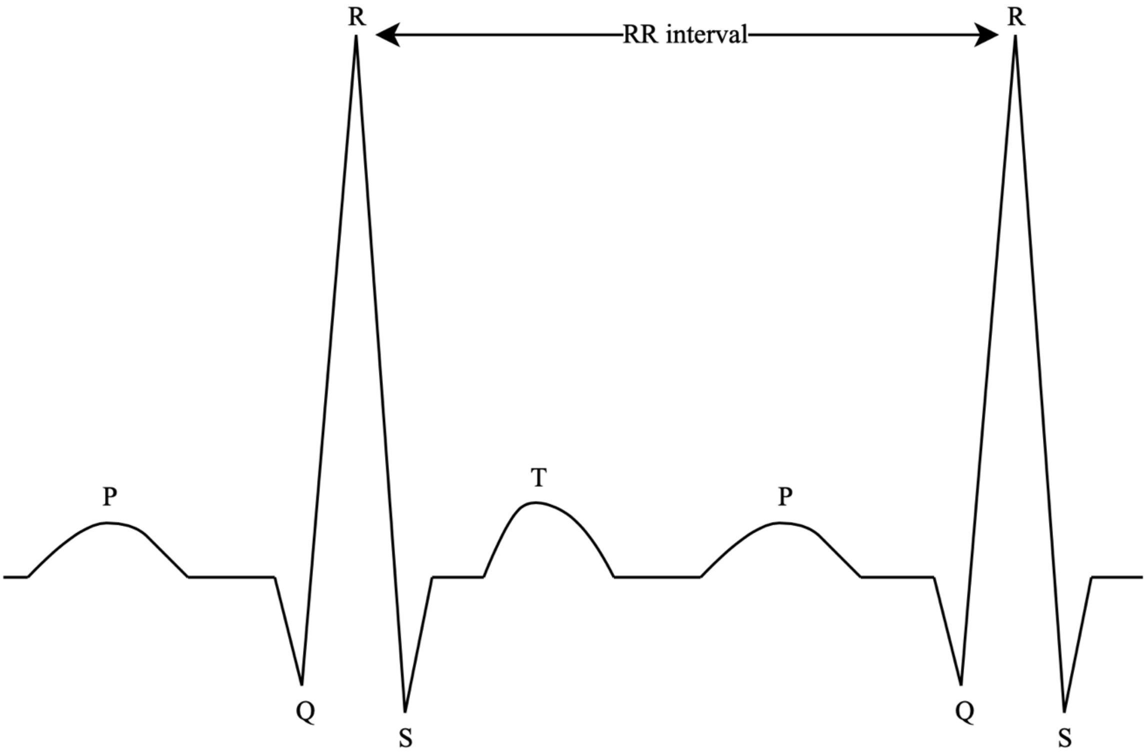
A 18-item sociodemographic questionnaire collects general information on the participant's family situation, medical history, current health status, hobbies, and familiarity with extreme environments.

The 32-item of the multidimensional assessment of interoceptive awareness (MAIA) evaluates interoceptive awareness. The scale is divided into eight sub-factors that measure awareness of uncomfortable, comfortable, and neutral body sensations (noticing), the response to sensations of pain and discomfort (not-distracting, not-worrying), the ability to regulate attention to body sensations and/or emotional states (attention regulation, emotional awareness, self-regulation), and awareness of mind-body integration (body listening, trusting) [15, 16].

2.2.2. Physiological measurements

Electrocardiogram (ECG) were recorded for a ten-minute period to extract heartbeat interval data (RR), with subjects in a sitting position (Figure 1). The HRV analysis followed guidelines reported in [24], which consider potential circadian variation, and used the *PyHRV* python library [32]. Raw ECG data were filtered using a finite impulse response band-pass filter. R peaks were automatically detected using the *BioSPPy* python library [33]. A Hamilton segmentation was performed on the filtered signal, followed by R-peak correction with tolerance set to 0.05. R-waves were manually examined to ensure correct detection. If an ECG sequence was overly noisy when visualizing the superposition of all QRS complex, the time interval was manually removed to improve data quality. RR intervals were automatically detected with the *hrvanalysis* module using linear interpolation, and manually corrected for artifacts and ectopic beats. A detrend of RR series was performed by subtracting the mean of RR intervals.

Figure 1
RR intervals extracted from ECG



Time domain HRV metrics included the RMSSD (Root Mean Square of Successive Differences between adjacent RR intervals).

2.2.3. Principal component analysis

A Principal Component Analysis (PCA) is a dimensionality reduction technique applied to the dataset in order to obtain new latent variables. Thus, the purpose of the PCA is to transform a dataset with potentially correlated variables into a new coordinate system where the variables are uncorrelated and ranked by their importance in explaining the variance of the original data. This is achieved by projecting the data onto a set of new orthogonal axes in a high-dimensional space that captures the maximum variance.

Given a dataset with N data points represented in a matrix X of size N x M, where each row x_i represents a data point with M features, the PCA involves the standardization of data $X_{std} = \frac{X - \mu}{\sigma}$, where μ is the mean vector and σ the standard deviation vector;

calculation of the covariance matrix, C $= \frac{1}{N} X_{std}^T X_{std}$; compute the eigenvalues λ_i and eigenvectors V_i ; choose the top k eigenvectors corresponding to the k largest eigenvalues; project data onto lower-dimensional space $X_{new} = X_{std} V_{selected}$, where X_{new} is the transformed data matrix in the reduced-dimensional space and $V_{selected}$ contains the eigenvectors corresponding to the selected principal components. The amount of information explained such that $\frac{\sum_{i=1}^{k} \lambda_i}{\sum_{i=1}^{M} \lambda_i}$ is the resulting explained variance, where k is the number of principal components selected and M the original number of features.

2.3. K-means algorithm

The goal of clustering algorithm is to identify structure in a data distribution. The k-means is a type of partitioning algorithm in non-supervised machine learning algorithm (i.e., learn from unlabeled data and extract similar patterns). In this case, $\overrightarrow{x_n}$ data are used for which no desired y_n values are available. In practice, each cluster C_k is defined by its centroid c_k, a vector of the input space, named prototype. Any x is assigned to the $C_k(x)$ cluster whose prototype is closest to x such that $k(x) = ArgMink\left(dist(x, c_k)\right)$. An Elbow curve, a heuristic method, was used to estimate the optimal number of clusters in a dataset when applying a clustering algorithm. More specifically, this is the point at which adding more clusters does not significantly reduce the within-cluster sum of squares.

2.4. Statistical analyses

Data analyses were performed with JASP (Amsterdam, version 0.16.3), an open-source software package that is used for both classical and Bayesian analyses. The Shapiro–Wilk test was used to determine whether data were normally distributed. When the analysis was significant, effect sizes were reported. Adaptation profiles were evaluated on interoceptive measures and on one HRV metrics, the RMSSD, linked to parasympathetic activity at baseline. ANOVA one-way analysis or Kruskal-Wallis test (i.e., depending on the normality of the distribution) were performed. Holm *post hoc* analyses were performed when the p-value was significant. Bayesian analyses were performed, by applying equivalent analyses for ANOVA one-way analysis. The

Bayesian Factor was calculated if no significant effect was detected. A low value provides support for the null hypothesis, and a high value indicates evidence in favor of the alternative hypothesis.

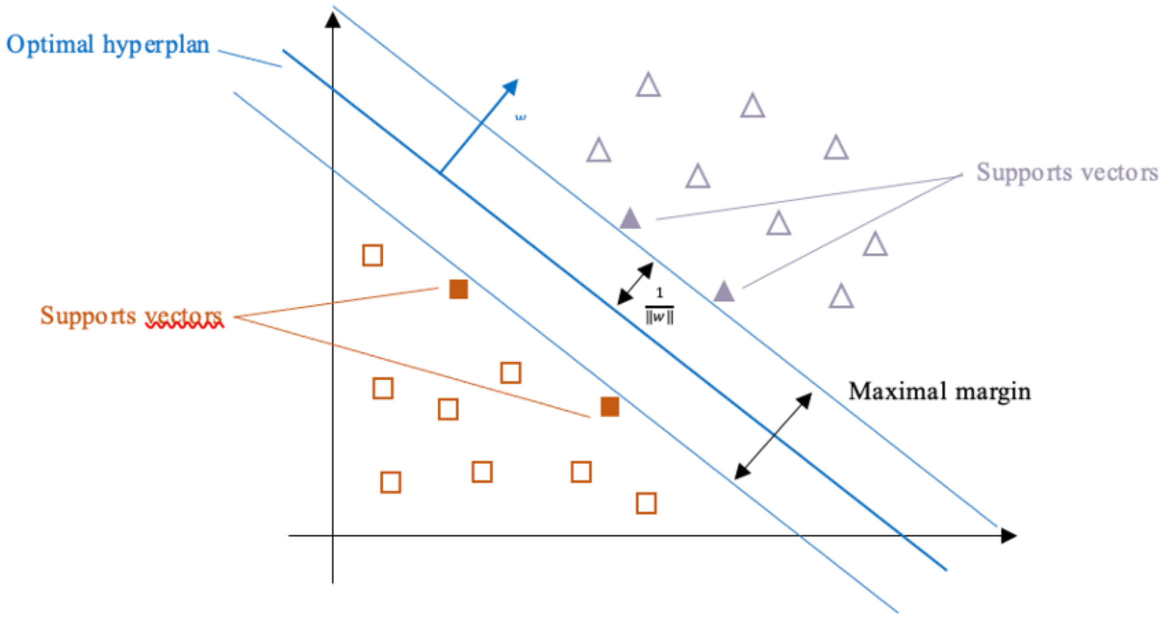
For all analyses, statistical significance was set at $p < .05$. A p-value between .05 and .07 was considered as evidence of a trend.

2.5. Support vector machine algorithm

The Support Vector Machine (SVM) algorithm is a classifier for separating two classes from each other, and thus by finding a hyperplane that best separates or predicts data points of different classes or values in a high-dimensional space. This is a supervised machine learning algorithm (i.e., analyze the labeled data and make predictions or classify data into different categories). In this case, $\overrightarrow{x_n}$ data are used in couple with desired y_n values. This algorithm tries to achieve the largest possible margin (i.e., minimum distance between an observation and a separating hyperplane) between data points of different classes. New data points can then be classified based on which side of the hyperplane they fall. There are founded on 2 main principles: (1) to achieve optimal linear separation to maximize the margin between the hyperplane and each of the two classes; (2) to use a kernel that transfers the original input space to a higher-dimensional space used to calculate the linear separation.

Given a training dataset with N datapoints $(x_1, y_1), (x_2, y_2), \ldots, (x_N, y_N)$, where x_i represents the feature vector of the i^{th}data point and y_i is the corresponding class label, the SVM aims to find a hyperplane described by the equation: $h(\vec{x}) = \overrightarrow{w^*} . \vec{x} + b^*$, where $(\overrightarrow{w^*}, b^*)$ is the solution to the constrained quadratic optimization problem (Figure 2).

Figure 2
SVM algorithm illustration



SVM is particularly useful when dealing with data that has multiple features or dimensions; less sensitive to outliers because it focuses on the support vectors that have the most impact on determining the hyperplane; can handle non-linear relationships between data points through the use of other kernel functions, allowing it to find complex decision boundaries; uses a regularization parameter to control the trade-off between maximizing the margin and correctly classifying data points. Moreover, this algorithm is useful in case of small examples [34].

2.6. Implementation

2.6.1. Missing data imputation

The dataset has missing data for multiple reasons (e.g., mission constraint). In order to reduce the noise from the missing data, imputation is an important part of data processing. In this work, we apply a randomize function. The purpose of this function is to introduce random noise to a value if it is missing (NaN). If the value is not missing (i.e., not NaN), the function returns the original value without any changes.

2.6.2. Data normalization

Data were normalized using the MinMaxScaler function which scales the data to a specific range, named x_{scaled} and in this case between -1 and 1.

$$x_{scaled} = \frac{x - \min(x)}{\max(x) - \min(x)}$$

This was performed to improve the numerical stability of the machine learning model.

2.6.3. Feature selection

A PCA was applied to the normalized data based on the delta of the psychophysiological features (i.e. RMSSD and interoceptive variables), noted M, and defined as $delta = M_{post\ mission} - M_{baseline}$. Three components were selected using 80% of the total variance and used to estimate clusters of mind-body adaptation by applying a non-supervised k-means algorithm and cluster labels were assigned to the data. Then, the SVM algorithm, based on the psychophysiological data at baseline, selects features for each cluster group separately based on how important they are for the classifier in order to separate classes. Specifically, the coefficients of the trained SVM model are extracted and stored in a list. These coefficients represent the importance of each feature in making classification decisions. Positive coefficients indicate that an increase in the feature value leads to a higher likelihood of belonging to a certain class, while negative coefficients indicate the opposite. This process provides a better understanding of which features are more influential in distinguishing between different clusters. The C regularization parameter is set to 1.0.

2.6.4. Model training

SVM classification is performed 1000 times with different random train-test splits. For each iteration, data were split into a training and a testing set. Each iteration involves training an SVM model with a linear kernel on a random subset of the data and then evaluating its performance using a test subset. The model was trained on 50% of the total dataset, which represents 42 individuals and tested on the remaining 50% (42 individuals). These proportions were chosen given the number of examples. As the k-means involves a multi-class problem, each pair of classes has been compared with the other to transform the multiclass problem on a binary classification problem to predict the M_{delta}; given its changes among the mission and its role in stress adaptation. The model is tracking the best accuracy achieved during the loop, along with the corresponding random state that led to that accuracy. If a better accuracy is found in any iteration, the best accuracy is updated to reflect the best new accuracy and the random state that produced it to identify which random state and corresponding model iteration resulted in the best accuracy when performing the SVM classification. A cross-validation was used to assess the generalization performance of the model and set to 10 because of the small dataset. The best model over the 1000 iterations was chosen.

2.6.5. Validation & Performance measurement

To evaluate the performance of the classifier, different measures were used. The confusion matrix assesses the performance of the SVM model on the test data and provides a detailed representation of the true positive (TP, i.e., correctly predicted as true), false positive (FP, i.e., false positive elements), true negative (TN, i.e., correctly predicted as false), and false negative (FN, i.e., false negative elements). Moreover, the classification report generates a comprehensive classification report including sensitivity (i.e., ability of the classifier to correctly identify non-adaptative profiles), specificity (i.e., ability of the classifier to correctly identify adaptative profiles), F1-score and accuracy (i.e., ratio of the total number of correct assessments to the Total number of assessments) for each class.

The sensitivity is calculated using:

$$Sensitivity = \frac{TP}{TP + FN}$$

The specificity is calculated using:

$$Specificity = \frac{TN}{TN + FP}$$

The F1-score is calculated using:

$$F1 = \frac{2 * TP}{2 * TP + FP + FN}$$

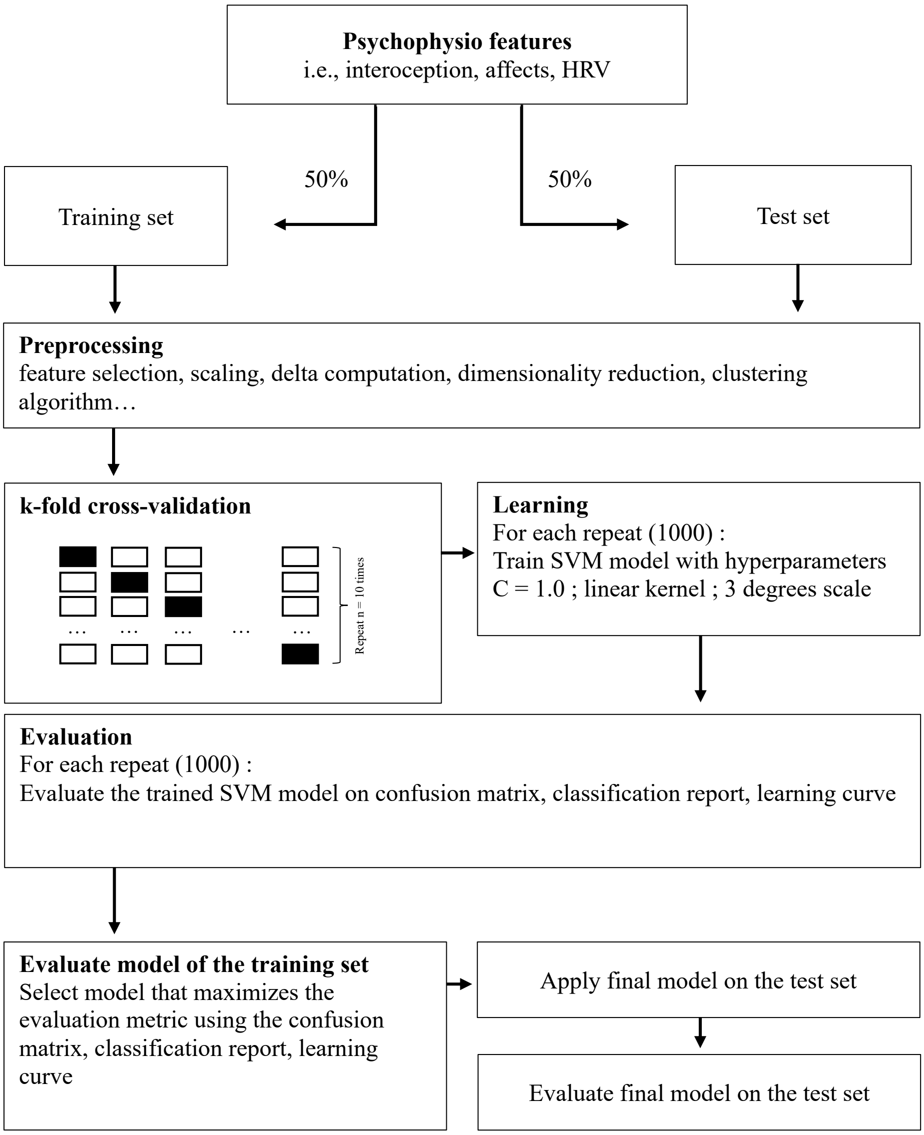
The accuracy is calculated using:

$$Accuracy = \frac{TN + TP}{TN + TP + FN + FP}$$

While the confusion matrix and the classification report provide insights into the model's ability to correctly classify different classes and its overall effectiveness, the learning curve identify trends in model performance and potential issues such as over- or underfitting and provide a visualization of the model's performance as a function of the size of the training dataset. This provides a quantitative assessment of the model's accuracy.

An architecture of the overall methodology is summarized Figure 3.

Figure 3
Schematic overview of the SVM model



3. Results

3.1. Characterization of adaptative profiles at baseline

Interoceptive awareness. No significant differences were found for noticing [F (2,81) = .019, p = .982, BF_{10} = .109], not-distracting [F (2,81) = .108, p = .898, BF_{10} = .117], not-worrying [F (2,81) = .176, p = .839, BF_{10} = .123], attention regulation [F (2,81) = .117, p = .890, BF_{10} = .117], emotional awareness [F (2,81) = .694, p = .503, BF_{10} = .186], self-regulation [F (2,81) = 1.867, p = .161, BF_{10} = .476], body listening [F (2,81) = .836, p = .437, BF_{10} = .206], and trusting [F (2,81) = .119, p = .888, BF_{10} = .118].

HRV. No significant difference was found for RMSSD [F (2,81) = .647, p = .526, BF_{10} = .180].

3.2. Adaptative labels development

PCA was performed on the M_{delta} recorded at baseline and post mission. Based on the three selected principal components (i.e., number explained components with an eigenvalue above 1; Table 3), the first factor which explained 45% of the variance, weighted negatively and positively on interoceptive perception (i.e., negatively for noticing, not-distracting, not-worrying, and positively for attention regulation and trusting, respectively). This factor, named interoceptive perceptive response, may indicate a disconnection of interoceptive perception level characterized both by a decrease in first levels of interoceptive perception associated and an increase confidence in attention to low-level perceptual interoceptive changes after the mission.

The second factor explained 21% of the variance and encompassed only positive weights on mind-body interoceptive integration (i.e., emotional awareness, self-regulation, body listening, respectively). This factor, named interoceptive body-mind integration, may reflect a reinforcement of the integration of highest levels of interoceptive information.

The third factor explained 8% of the variance and encompassed positive weights on the following interoceptive variables (i.e., not-distracting, not-worrying, and trusting, respectively), negative weight on the body listening interoceptive variable and positive weight on the parasympathetic measure (i.e., RMSSD). This factor, named neuroceptive response, may be understood as an unconscious perception of the level of safety induced by the ANS response. The body response to constraint may translate an increase in vagal system as well as a better interoceptive perception, except for the body listening as the neuroception is an unconscious process.

The results of the PCA analysis are presented in Table 3.

Table 3

PCA loading matrix based on psychophysiological delta

Features*	Factor 1	Factor 2	Factor 3
M1	**-0.603084**	0.193812	0.292055
M2	**-0.492501**	0.014933	**0.331470**
M3	**0.308100**	-0.266251	**0.400273**
M4	**0.404623**	0.295373	0.144089
M5	0.111615	**0.437078**	0.083937
M6	-0.036385	**0.502032**	0.142423
M7	-0.020308	**0.553175**	**-0.449106**
M8	**0.333254**	0.223559	**0.532645**
RMSSD	-0.099166	0.070882	**0.333339**

*Correlations between each features and the factors are shown.

M1 = noticing; M2 = not distracting; M3 = not worrying; M4 = attention regulation; M5 = emotional awareness; M6 = self-regulation; M7 = body listening; M8 = trusting.

Then, a k-means was employed on the overall variables used in the PCA in order to create profiles of subjects (Figure 4). The Elbow curve indicates an optimal partitioning with 3 profiles. No significant differences among profiles were found at baseline.

The yellow profile (class 0) included 35 subjects (41.66% of the population). This profile has negative values on factor 1 targeting interoceptive perceptive response (i.e., except for one outlier subject who has a positive value of 0.33 on this axis) as well as on factor 2 targeting interoceptive body-mind integration. Nevertheless, the yellow profile scored on all the scale of the third factor, ranging from -0.47 to 0.8 (i.e., 14 negatives and 21 positives). Thus, this profile has a decrease in first level of interoceptive perception as well as in interoceptive body-mind integration, and thus in all levels of interoceptive awareness. However, the third factor is not conclusive to discriminate this profile on neuroception even if most of these subjects scores positively.

The green profile (class 1) is composed of 21 subjects (25.00% of the population). This profile has positive values on factor 1 targeting interoceptive perceptive response as well as negative values on factor 2 targeting interoceptive body-mind integration (except for four outliers who scored 0.12 to 0.47 on the axis). Also, the green profile scored on all the scale of the third factor, ranging from -0.77 to 0.67 (i.e., 12 negatives and 8 positives). Thus, this profile has an increase confidence in attention to low-level perceptual interoceptive changes but a decrease interoceptive body-mind integration. As the yellow profile, the third factor is not conclusive to discriminate the green profile on neuroception even if most subjects scored negatively.

The purple profile (class 2) exhibited 28 subjects (33.33% of the population). This profile has negative values on factor 1 targeting interoceptive perceptive response (except for three outliers' subjects who has positive values of 0.06, 0.32, and 0.36 respectively on this axis) as well as positive values on factor 2 targeting interoceptive body-mind integration. Also, the purple profile mainly scored negative the third factor, ranging from -0.68 to 0.66 (i.e., 20 negatives and 9 positives). Thus, this profile has decrease in first level of interoceptive perception but an increase in body listening resulting in a decoupling between deteriorating interoceptive perception and increasing body-mind integration. Compared to the two previous profiles, this one appears to mostly impair neuroception with gains in body listening, suggesting an unsafe neuroception.

Table 4 encompasses the representation of space analogs among the k-means profiles.

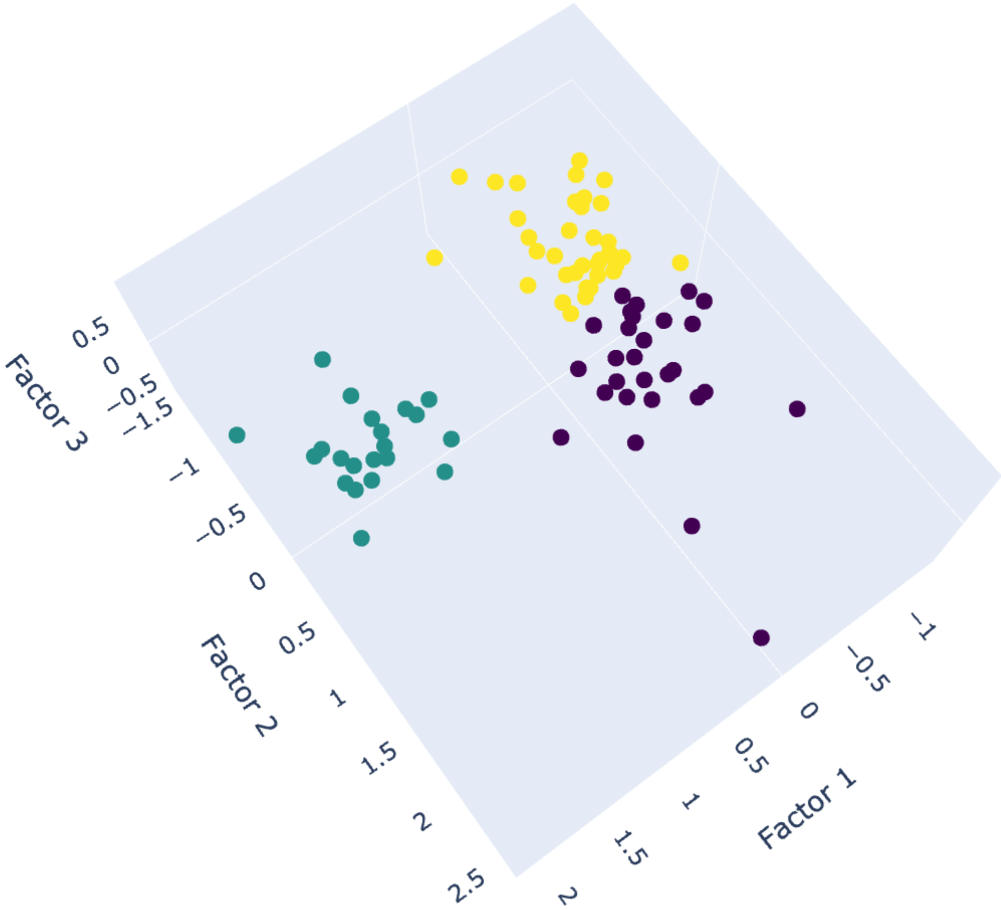
Table 4

Representation of space analogs among profiles

Space analogs*	0	1	2
ENACT	11	-	6
SSBN	10	-	9
RAD'LÔ	-	21	-
ANTIDOTE	14	-	13

*ENACT = parabolic flights in microgravity; SSBN = sub-surface ballistic nuclear-powered missile; RAD'LÔ = simulation of survival at sea; ANTIDOTE = simulation of medical intervention under CBRN attack with protective equipment.

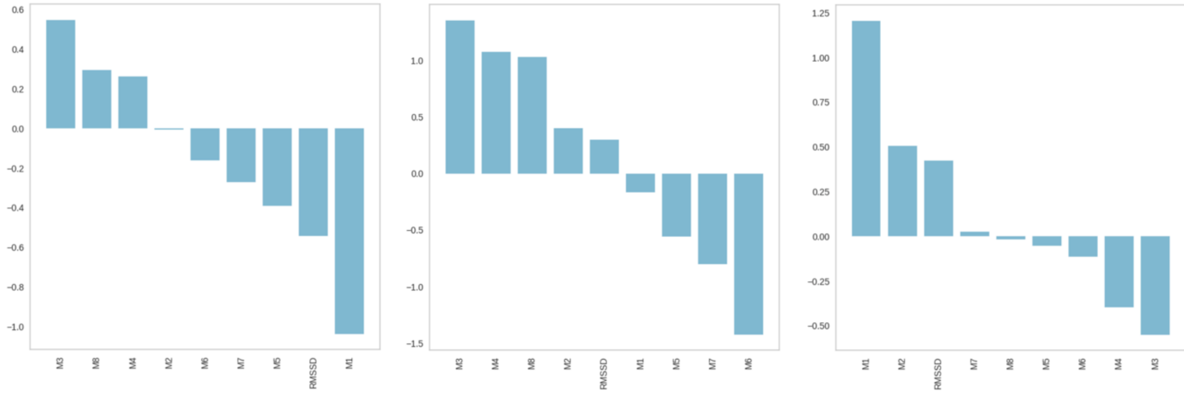
Figure 4
Repartition of subjects between classes



3.3. Model performance & evaluation

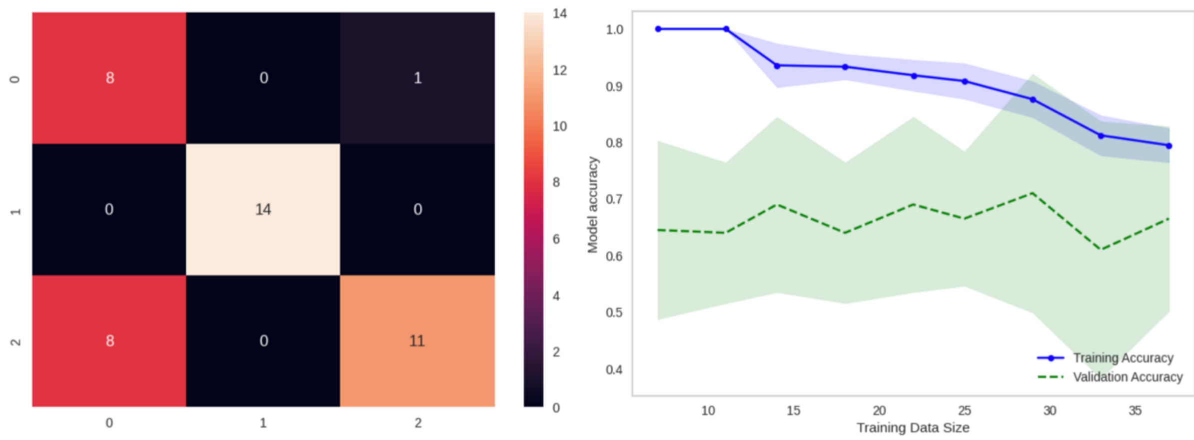
Psychophysiological features at baseline were used as input to train the SVM machine learning algorithm. The contribution of each feature (i.e., same features involved in the PCA, and the k-means recorded at baseline), and thus the selection of important features was performed to observe which one predicts the M_{delta}. Figure 5 shows the importance of each feature computed for each paired of class (Figure 5).

Figure 5
Importance features obtained with SVM for each pair of class



Thus, the classification performance rates for SVM are 100% specificity and 79% accuracy according to the average model. The confusion matrix shows that almost all examples are learned. The learning curve and the validation score seem to converge at the end. The learning curve and the validation score fail to converge (Figure 6).

Figure 6
Confusion matrix and learning curve



The classification results obtained by SVM is reported in Table 5.

Table 5

Classification report

Class*	SEN (%)*	F1-score (%)	PRE (%)*
0	.89	.64	.50
1	1.00	1.00	1.00
2	.58	.71	.92

0 = yellow; 1 = green; 2 = purple; SEN = sensitivity; PRE = precision.

4. Discussion

This study successfully applied machine learning techniques to predict profiles of adaptation after the mission based on psychological and physiological states recoded before mission's departure in space analogs. In addition to the identified risk exposures that were already confirmed in previous studies [e.g., 35, 36], it is necessary to detect crew's members who will have the most deleterious adaptative response over the mission.

Three individual response profiles were identified by a PCA based on the evolution of psychophysiological features on return compared to the day before the start of the mission followed by kmeans using the three PCA factors. The SVM classification model revealed that it was possible to predict the type of response of individuals using the baseline of psychophysiological features.

Thus, based on PCA, we were able to identify three factors. The first characterizes a disconnect between the lowest levels of interoceptive information processing. Individuals with a positive coefficient on this factor degrade their interoceptive perception in terms of *noticing* (i.e., awareness of body sensations), *not-distracting* (i.e., distracting from sensations of pain or discomfort) while increasing their interoceptive functioning in terms of *not-worrying* (i.e., any worrying or emotional distress in presence of negative stimuli), *attention regulation* (i.e., ability to regulation attention), as well as *trusting* (i.e., confident of body sensations) and inversely. The *noticing* sub-factor was positively correlated with the notions of present moment, the experience of interoceptive stimuli, and mind-body listening [16]. The *not-distracting* sub-factor was positively correlated with awareness of a loss of mind-body connection, acceptance of negative bodily sensations, how emotions impact behavior, notions of present moment and bodily dissociation. The *not-worrying* sub-factor was positively correlated with acceptance of negative bodily sensations, how emotions impact behavior, and efficient emotional regulation (e.g., less worry, acceptance of emotions, access to emotional regulation strategies, better impulse control, lower anxiety). The *attention regulation* sub-factor was positively correlated with observational abilities, stability, awareness, listening, acceptance of bodily and emotional sensations, and absence of rumination. The *trusting* sub-factor was positively correlated with observational abilities, listening to one's bodily sensations, emotional management, stability as well as low levels of anxiety and bodily dissociation [16]. An improvement in levels of *not-worrying*, *attention regulation*, and *trusting* combined with a deterioration in levels of *noticing* and *not-distracting* might therefore be associated with an acceptance of negatively valued stimuli while having a reduced ability to anchor oneself in the present moment. This factor may reflect an alteration in the first level of interoceptive processing, and conversely, greater confidence in attention to low-level perceptual interoceptive changes.

The second reflects interoceptive body-mind integration. Individuals with a positive coefficient on this factor increased their interoceptive level of *emotional awareness* (i.e., awareness of the body sensations and emotional states' connection), *self-regulation* (i.e., psychological distress regulation by paying attention to body sensations), *body listening* (i.e., listens to the inner body) and inversely [16]. The *emotional awareness* sub-factor was positively correlated with observational abilities, listening to body sensations and emotional management [16]. The *self-regulation* sub-factor was positively correlated with observational abilities, mindfulness skills for listening to the body, emotional management, as well as experiencing low levels of anxiety [16]. The *body listening* sub-factor was positively correlated with observational abilities, body listening, mindfulness skills to one's internal sensations, as well as low levels of rumination and body dissociation [16]. Therefore, this factor reflects, in its positive component, a more efficient processing as well as integration of interoceptive information, enabling a strengthening of mind-body integration and thus, body awareness.

The third involves a neuroceptive response. Individuals with a high coefficient on this factor gain in the interoceptive sub-factors *not-distracting* (i.e., distracting from sensations of pain or discomfort), *not-worrying* (i.e., any worrying or emotional distress in presence of negative stimuli) and *trusting* (i.e., confident of body sensations) as well as in parasympathetic functioning (i.e., RMSSD) but they lose the *body listening* interoceptive sub-factor (i.e., listens to the inner body) and inversely. The shared interoceptive sub-factors *not-worrying* and *trusting* in factor 1 and 3 may be explained in two ways. First, two versions of the MAIA were used in the studies that composed our dataset. Mehling and colleagues initially developed a first version in 2012 [16] and then a second in 2018 [15, 37] to improve the quality of the scale. Specifically, the *not-worrying* sub-factor was one of those modified in the new version of the questionnaire, potentially introducing a bias into our results. Furthermore, the *trusting* sub-factor appears to be decorrelated from the other MAIA dimensions. A recent study showed an association between advancing depression and loss of trust in bodily sensations [38]. The authors went further, arguing that the loss of the *trusting* sub-factor would initiate the alteration of subsequent interoceptive processes. The positive component of factor 3 might thus translate into enhanced neuroception, and inversely for its negative component. Neuroception involves the perception of safety/insecurity sensations from the environment through the ANS as introduced by Porges [39]. This neural process occurs exclusively unconsciously. Consequently, a negative axis of *body listening* can support this line of reasoning, as it implies a conversely conscious process of listening to the body. The RMSSD is considered as a break on stress and thus a marker of stress vulnerability [24, 27, 35]. This type of response is important when the environment constraint is important to express an adaptative behavior.

From these factors, three profiles were defined on the basis of the results of the Elbow curve, which indicates the optimal number of clusters. Individuals in the yellow group have impaired processing of all levels of interoceptive information and reveal significant inter-individual variability in their neuroceptive response. This profile appears to display the characteristics of an interoceptive dysfunction in coping with mission constraints. This dysfunction appears to be associated with an improvement in neuroception for some, and a deterioration for others i.e., yellow group). These last individuals may evolve towards a neuroception that increases insecurity as the environment becomes more stressful. Those in the green group have a disconnection in their interoceptive perception, evidenced by an increased reliance on attention to low-level perceptual interoceptive changes and impaired processing of high-level interoceptive information.

As with the yellow profile, there was considerable inter-individual variability in their neuroceptive response. Nevertheless, a greater proportion of individuals show a loss of neuroceptive response. Nevertheless, a greater proportion of individuals show a loss of neuroceptive response. Individuals in the purple profile have a disconnection of their interoceptive perception, evidenced by an impairment of the first level of interoceptive processing and an improvement in mind-body integration. Moreover, this is the group for which many subjects impaired their neuroception (71.42%).

The distribution of space analog environments for each profile demonstrates that the green profile is exclusively composed of participants from the RAD'LÔ study. The distribution of subjects for the yellow and purple profiles is equivalent between ENACT, SSBN and ANTIDOTE exclusively. Survival at sea represents the environment with the highest stress intensity and has been considered one of the most complex survival situations [40] for which stressors are most virulent [41, 42]. Chen and colleagues [43] studied the adaptation of overwinterers at several polar stations. They found that the more severe the environmental characteristics, the more deleterious the effects. The response to survival at sea is associated with bodily dissociation and heightened hypersensitivity to stimuli in the face of an exacerbated sensory environment [44]. Thus, the more extreme the environment, the greater the environmental demand and the more complex the adaptation to cope with it. Thus, the more extreme the environment, the greater the effort required to adapt to these stressors.

The results of the machine learning model capture and illustrate this complexity. SVM is frequently used to model stress [45] and is an effective classifier for assessing physiological signal using cardiac biosignal [46, 47]. To the best of our knowledge, it has been little used for and interoceptive sensitivity. SVM is considered one of the best classification techniques used to model stress [48], particularly in the case of small samples [34]. This approach offers high accuracy and low computational power. By bringing together different types of space analogues, we were able to identify the 3 interoceptive-physiological response profiles from the baseline whereas both no difference was observed between the populations on the psychophysiological baseline level. Given the possible biases inherent in the collection environment, these results are promising given the small number of training examples. Stress is a complex state that can use information from multimodal sources to reliably assess vulnerability and adaptation to stress. Moreover, the psychophysiological temporalities of the complex regulations involved in the stress response are different.

The classification report shows that the model performs well for the green class, achieving high sensitivity, F1-score, and precision. For purple class, the precision and F1-score performed better, and the sensitivity performed lower than the yellow class. This report provides a comprehensive view of the model's performance for each class, considering both false positives and false negatives. Nevertheless, the validation accuracy shows fluctuations. This behavior can suggest that the model's performance is not enough stable and might be sensitive to variations in the validation dataset. This may be explained by several factors such as noise, and outliers. Nevertheless, the split into a training and testing dataset is useful in case of small sample size [49]. Moreover, the learning curve may highlight an unrepresentative dataset. The dataset may not capture the statistical characteristics between both the train and the validation dataset, and finally fall to provide sufficient information to learn the classification problem. The promising 79% accuracy of the SVM may be explained by the difficulty to learn from inter-individual differences between subjects. This may be increased by our small sample size (i.e., even if this number is important for space analogs studies). From our 84 subjects, only 42 composed each training and validation set. Furthermore, the quality of the ECG signal can interfere with the classification result. A noisy signal may induce lower classification accuracy [34]. The signal entropy of some recordings can lead to redundant or overlapping information. This reduces classification performance even though features in the non-linear domain are more robust than those in the linear domain. The choice of a linear kernel SVM classifier can therefore model more naturally these types of variables (using a small number of free parameters). Conversely, the SVM can perform due to a less obvious separation between the two classes. SVM may be weakened when its boundary between two classes is clear, while its performance is improved when the boundary is unclear. Vectors furthest from the hyperplane have more obvious class labels. They can calculate the hyperplane separation between the two classes more accurately. Further research is needed and will be pursued to more accurately predict adaptative profiles. Nevertheless, recent research highlights that stress-detection models based on physiological features performed better in laboratory conditions, than in ecological context [50]. This result was consistent among the included studies in their analysis [50]. Thus, our model may not generalize well to data from unseen subjects do the high inter-individual variability, as already reveal in the literature [1].

Overall, this study supports the importance of offering specific support to maintain operational capacity. This study highlights that we are able to predict adaptative profiles over a space analog missions based on psychophysiological measures before the mission. Crew members with a lower ability to adapt are the ones that should receive special training programs. These programs need to be carefully adjusted to each individual's ability to adapt to their profile and/or the environment to which they will be exposed, particularly when this involves high-intensity stresses. The treatment of interoceptive informations' seems informative to classify crew members during a mission in space analogs. Thus, interoceptive pathways are involved in adaptation. These results confirm the previous findings that associated interoception to mental health well-being [12], and that interoception may be beneficial to deal with the stress response over the long term [18, 29].

The limitation of using the MAIA [15] lies in the subjective assessment of individuals' interoceptive sensitivity. Although this tool seems promising in its latest version, a more finobjective assessment e of the integration of interoceptive information would have been favorable for improving profile discrimination. Moreover, only the purple profile tends towards physiological adaptation, as evidenced by high parasympathetic functioning with the RMSSD. This result illustrates a close link between the psychological and physiological neuropathways leading to allostasis, and the importance of measuring them to better understand the adaptive or non-adaptive response of individuals subjected to stressful environments.

Nevertheless, this study shows that it is complex to identify one profile that will be perfectly adapted and another that will be increasingly vulnerable over the course of a mission. We are dealing with three groups of adaptation to space analogs environments. They reflect the reality of the field and the challenges of the mission, as suggested by the RAD'LÔ group. Although we have a small sample of 84 individuals, these results suggest that further study is needed to predict who is most at risk. This tool could be used as an initial « triage » tool, but should not be used as a substitute for screening by a medical team. Inter-individual variability remains very significant and is particularly highlighted by all the profiles on the third axis of PCA. This work cannot therefore replace pre-departure screening at the moment. A search for the variables that account for the large variance needs to be explored. More objective measurement tools are needed, particularly for assessing the interoceptive response. Among these profiles, the best as well as the most vulnerable are observed. Thus, even if individuals are highly selected in these unusual environments, and on a similar selection process, it is complex to predict their adaptive capacities. A recently published review [1] discussed the lack of a consensus model to highlight the psychocognitive mechanisms that lead to adaptation, due to the multifactorial nature of adaptation, significant inter-individual variation, and inter-study bias.

This work represents a first step in the identification of several potential predictors involved in the adaptation process during a space analog mission. Several approaches and countermeasures should be studied in the light of these results if confirmed.

5. Limitations

This study presents several major limitations. The first is the small sample size, an imbalance between male and female, and right- and left-handed subjects. Studying such a population is complex, both in terms of time constraints, and access to infrastructure and personnel (i.e., operational constraints, attendance). Both the scientific team and participants must be flexible to run experiments in space analogs. These results need to be confirmed with a larger dataset, which could be collected over several years (in the context of a PhD the time constraints add a lack of recorded measures). Secondly, our results are not reproducible beyond the specific experimental conditions and cannot be generalized. Space analogs were atypical ICE and EUE environments involving specific stresssors. Thirdly, this study involves a binary classification problem. Adaptation in multifactorial and a multi-class problem might perform better to predict delta based on psychophysiological functioning before and after the mission. Fourth, interoceptive data (i.e., collected through questionnaires) are subjective measures, and implicates two different versions of the MAIA questionnaires. Intelligent sensors would provide more objective measures of subjects' adaptation to extreme environments. The use of tool that notably evaluate emotional regulation would be informative regarding its involvement in interoceptive and ANS response [29]. Fifth, different ECG devices were used to collect RR intervals. The use of a single gold-standard ECG may increase the reliability between subjects in the dataset.

6. Conclusion

The present study is one of the first to test a psychophysiological adaptation prediction in space analogs based on baseline features. The theoretical framework chosen is based on interoceptivo-vagal integration, which is recognized as an important model of adaptation to stress. Various space analogs environments were compiled to assess the possibility of extrapolating results to these singular environments. These results are in line with the complex nature of multifactorial adaptation. They suggest a modification in the processing of interoceptive information over the course of the mission, as well as a modulation of vagal ANS responses. It is essential that this research into the most predictive variables under stress continues, considering the limitations of the field. This factor should be included as a modality in machine learning models. Also, the results show that despite a similar selection process based on this ability to evolve in a constrained environment, it is complex to predict the adaptive capacities of individuals. Only by studying adaptation and trying to understand its mechanisms can efficient countermeasures be established to maintain crew health.

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Synthèse des résultats principaux

L'étude AI avait pour objectif d'identifier des profils d'adaptation chez les individus, professionnels et non professionnels, en environnement ICE/EUE, en utilisant une évaluation du fonctionnement intéroceptifs, physiologiques avant le départ en mission. Un second objectif était d'appliquer les outils de l'AI pour évaluer leur apport dans des situations de terrain présentant des contraintes proches bien que différentes. L'AI permet de traiter une quantité de données relativement importante et en temps réel. Sans intervention humaine, elle peut ainsi catégoriser et prédire des phénomènes complexes à partir de données existantes. Cette possibilité rend cet outil indispensable à l'avenir en ouvrant la voie à l'identification de réponses d'adaptation dans des situations écologiques et donc en offrant des opportunités d'intérêt pour caractériser des profils d'individu.

Les résultats de cette étude exploratoire ont mis en évidence la possibilité de prédire la qualité d'adaptation d'individus ayant vécu une situation en analogue spatial grâce à l'AI à partir de leur fonctionnement psychophysiologique avant le départ. Une des plus-values de ce travail tient à la confirmation du rôle de l'intéroception. De plus en plus d'études montrent son importance pour la santé, et notamment comme un facteur transdiagnostique de pathologie en lien avec le stress (Khalsa et al., 2018). Dans cette étude, l'intéroception a été mesurée par le questionnaire de référence mais plusieurs outils objectifs de la qualité de l'intéroception seront en cours de validation et pourrait permettre d'améliorer les prédictions d'adaptation.

Ainsi, nos résultats soulignent le potentiel du *machine learning* pour pouvoir caractériser des profils d'individus mais également la nature complexe et multifactorielle de l'adaptation. Ils valident l'intérêt de cibler des contre-mesures visant l'intégration cœur-cerveau pour maintenir l'adaptation en environnement contraignant.

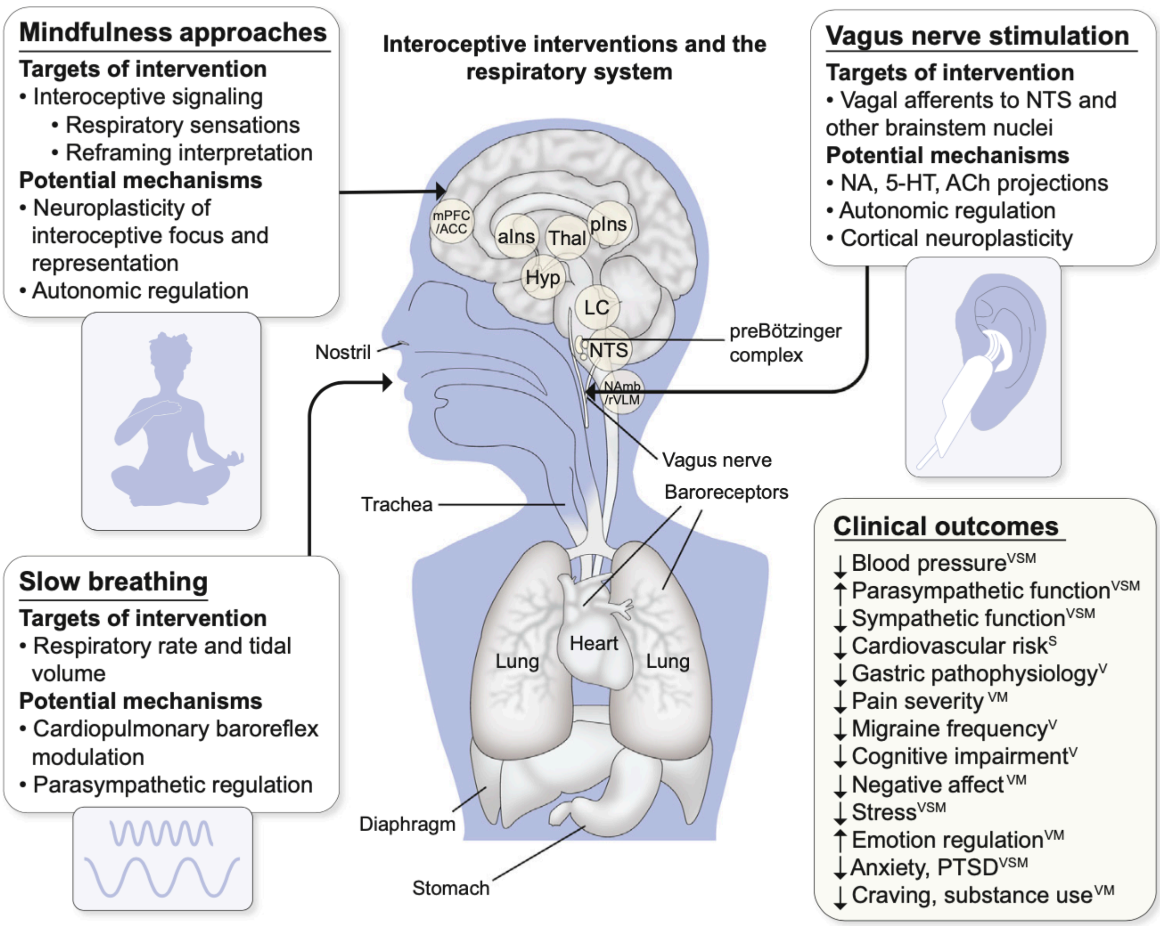
Contre-mesures de santé

Ces dernières années, un nombre croissant d'études scientifiques s'attachent à explorer les potentiels contre-mesures pour maintenir la santé des astronautes qui participeront aux vols spatiaux de longue durée (*long duration space flight*, LDSE). En 1998, le Comité de biologie spatiale et de médecine a proposé de considérer les besoins en contre-mesures selon plusieurs temporalités : (1) avant le vol avec l'apprentissage et l'entraînement de stratégies de coping ; (2) au cours du vol avec le monitoring en temps réel et la médecin personnalisée, les interventions avec l'équipe médicale au sol, la communication avec les familles ; (3) après le vol avec l'évaluation de l'état de santé et le débriefing de mission. Récemment en 2016, Manier et Colas ont souligné la nécessité d'implémenter un sas psychologique avant le départ et au retour et insistent sur le besoin de développer des vaisseaux qui répondent aux défis environnementaux et de mission. Néanmoins, les contre-mesures doivent être considérées comme une aide dynamique qui peut être ajustée aux besoins individuels identifiés avant la mission, mais aussi en fonction de la durée et du type de la mission. Le constat de nos études souligne qu'il est fondamental d'utiliser une approche intégrative avec plusieurs approches méthodologiques pour mieux surveiller la santé et adapter les contre-mesures. Chaque individu ayant à la fois des réponses physiologiques qui lui sont propres et une quantité de ressources mobilisables différentes pour faire face à un stresseur, il est indéniable que l'emploi de mesures personnalisées est fondamental pour maximiser les bénéfices des contre-mesures. C'est donc cette meilleure compréhension de l'adaptation aux ICE/EUE qui permettra un suivi pertinent de l'équipage avec un panel d'outils suffisamment flexibles pour s'adapter aux profils de l'équipage en fonction de la temporalité de la mission.

Différents types d'interventions ont été investigués afin d'augmenter la sensibilité intéroceptive. Weng et al. (2021) ont cité trois niveaux d'actions ayant des répercussions sur les processus intéroceptifs (Figure 24) : (1) psychologique comme les pratiques visant à renforcer la *mindulness* (i.e., attention portée aux sensations corporelles), (2) comportemental comme le *slow breathing pattern* (i.e., ~5 respirations par minute via une activation des barorécepteurs cardiopulmonaires qui inhibe le SNS) ; (3) neural comme la stimulation du nerf vague (*vagus nerve stimulation*, VNS ; i.e., activation du réflexe parasympathique vagal) visant des bénéfices multiples sur l'organisme et ainsi sur le fonctionnement et le comportement adaptatif.

Si ces trois axes de contre-mesures impliquent tous le fonctionnement intéroceptif, l'interaction complexe entre les voies ascendantes et descendantes du système intéroceptif offre de nombreuses approches non pharmacologiques pour des interventions ciblées afin d'améliorer les capacités adaptatives. Son amélioration est liée à une régulation des afférences sympathiques, à une meilleure acceptation sans jugement des signaux corporels et à un sentiment de soi fondé sur l'expérience des sensations physiques dans le moment présent (Figure 24). En outre, les contre-mesures devraient cibler un renforcement et/ou une augmentation de la communication de l'axe corps-cerveau.

Figure 24
Interoceptive interventions (Weng et al., 2021)



Dans le cadre de ce travail, trois approches de contre-mesures pour les LDSE ont été envisagées : (1) une approche basée sur les données de la littérature sur le fonctionnement *mindfulness* (MD) au regard des effets positifs de ce fonctionnement en termes d'adaptation au stress et en termes de réponses biologiques, physiologiques et psychologiques et donc de santé (PRESENCE) ; (2) une approche fondée sur l'activité immersive qui a montré, par l'enrichissement sensoriel visé, des bénéfices dans de nombreuses pathologies, notamment sur les émotions négatives (APTICE) ; et (3) une approche fondée sur la stimulation transcutanée auriculaire du nerf vague (*transcutaneous auricular vagus nerve stimulation*, taVNS) pour une amélioration du tonus parasympathique, qui semble démontrer de nombreux bienfaits pour la santé (SATE).

La première approche rassemble un travail de synthèse de la littérature avec la volonté d'évaluer la pertinence du fonctionnement mindful lors des LDSE. Dans la mesure où la *mindfulness* semble être associée à une meilleure sensibilité aux signaux intéroceptifs, que nous avons montré en étroite relation avec les processus extéroceptifs et émotionnels qui participent à l'état de santé, il semble évident de se demander si une intervention améliorant la MD ne serait pas appropriée. Actuellement, aucune étude ne s'est focalisée sur la MD dans le contexte des missions spatiales. La plupart des études sur le sujet en milieu ICE/EUE sont issus des milieux analogues ou d'expérimentations militaires.

L'étude PRESENCE avait deux objectifs principaux : (1) conduire une réflexion qui examine le fonctionnement de la MD comme une caractéristique de l'individu propice à l'émergence d'une adaptation durable en ICE/EUE ; et (2) pointer les nouvelles technologies qui améliorent le fonctionnement de la MD.

Mindfulness for Adaptation to Analog and New Technologies for Long-term Space Missions

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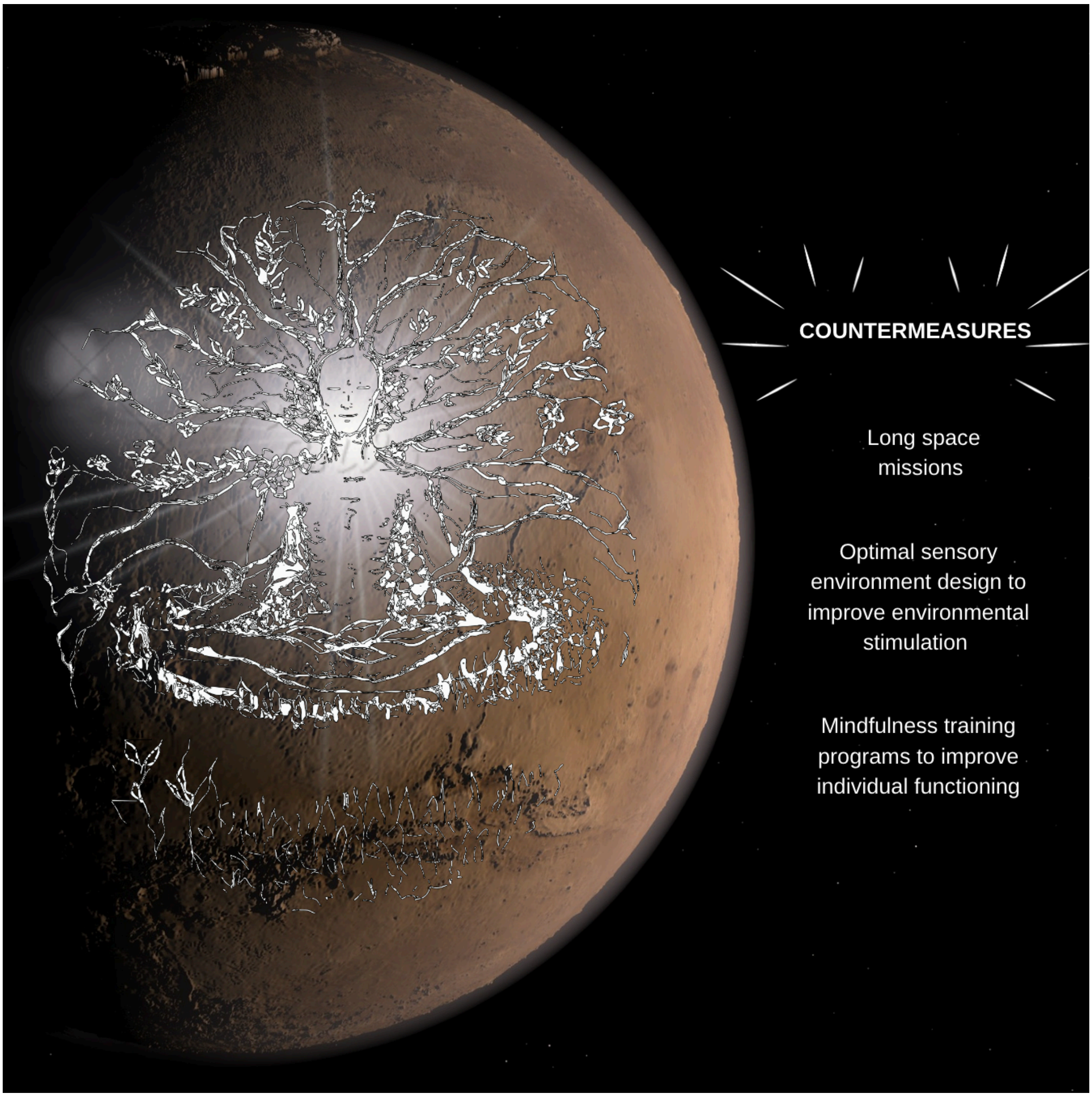
Abstract

Long-term space missions require a good understanding of human adaptation to hostile environments in space. Some professional environments have space constraints that are isolating, confined, extreme, or unusual constraints. They can serve as space analogs for studying challenge adaptation as their environmental constraints disrupt the balance between the demands of the environment and the resources mobilized by individuals. This disruption in homeostasis leads to increased stress, decreased performance, and poor overall health for these professionals. Nevertheless, as analogs, these professional environments can also offer information for better identifying the individual psychological and cognitive resources that are effective in adapting to the constraints caused by these exceptional environments. Studies suggest that mindfulness (i.e., awareness that emerges by paying attention purposefully, in the present moment, without judgment to the experience that is unfolding moment by moment) may be a relevant candidate for dealing with these issues. Thus, we address mindfulness as a relevant psychological resource to face the constraints of space missions based on experiences in analog environments and military contexts. We propose to open discussions on new countermeasures focused on developing mindfulness, especially through the use of new technologies (e.g., « immersive reality » and others), to increase adaptation to the space environment and offer programs tailored to the needs of astronauts for long space journeys.

Figure 25
Graphical abstract PRESENCE



Keywords

Analogs, Countermeasure, Mindfulness, New technologies, Space missions

1. Introduction

At the onset of long space missions, the scientific community is in turmoil, trying to find ways to repel the obvious extreme that such an environment represents (Driskell et al., 2020). Space represents an imminent threat of death to humans who risk their performance and lives by venturing into it. Nevertheless, we are constantly trying to find ways to survive, even in the most hostile environments. This survival requires the involvement of several processes that allow for the most authentic adaptation of a human to their environment.

Isolated and Confined Environments (ICE) and/or Extreme and Unusual Environments (EUE) are professional operational environments experienced by deep sea divers, polar winterers, or submariners through professional engagement. They are marked by extreme climates, danger, limited facilities, and supplies, isolation of loved ones, and required interaction with others (Harrison and Connors, 1984; Manzey and Lorenz, 1998). These environments are often referred to as « extreme », « strange », « exotic », « abnormal », or « stressful environments » (Ross, 1974; Bachrach, 1982; Harrison and Connors, 1984; Shimamiya et al., 2005). Paulus and Stein (2010) define « extreme environments » as an external context that exposes individuals to demanding psychological and/or physical conditions and which may have profound effects on cognitive and behavioral performance. More recently, Ramachandran and Paul (2019) characterize these environments as situations that place high demands on the individual's physiological, emotional, cognitive, and/or social treatment resources. ICE and EUE environments have long been considered analogs of space environments and have been used to extrapolate some of the adaptation mechanisms of astronauts (Suedfeld and Mocellin, 1987; Rivolier, 1997). Furthermore, in preparation for long-term and deep space exploration, it is critical to test solutions to meet the complex needs of life using Earth-based life support systems. Life Support Systems (LSSs) are designed to provide the required environment for human beings to survive in outer space or isolated environments (Jones, 2003). As space habitats move farther from earth, resupply of life-support materials will become increasingly difficult and expensive. The complete regeneration of life-support materials then becomes of interest; the most reliable and efficient means of replacing used materials is bioregeneration. This process is centered on the use of a primary biological process, photosynthesis, as part of a physical/chemical system that is capable of continuously supplying the food, oxygen, and potable water required by a crew and of removing all waste materials, including carbon dioxide, from the crew's environment. Controlled Ecological LSSs (CELSSs) are LSSs driven by the use of artificial ecosystems based on advanced control strategies to guarantee their long-term operation, including the provision of food, which is not possible with purely physicochemical LSSs (Schwartzkopf, 1992). The relative isolation and confinement of these facilities, which are often organized with interconnected modules, allow for rigorous field studies and human factors research that is useful for interdisciplinary approaches that investigate multi-system adaptation in human models (Jones and Kliss, 2010; Tafforin, 2015; Yuan et al., 2019). The ICE and EUE environments expose the crews to cognitive, psychological, and sensory disturbances (Kanas et al., 2013; Basner et al., 2014; Pagel and Choukèr, 2016; Kim et al., 2018; Weber et al., 2019; Flynn-Evans et al., 2020; Moraes et al., 2020; Palinkas and Suedfeld, 2021). The exceptional nature of these terrains means that individuals participating in missions must experiment and implement several processes to adapt. Everything that might have existed before (i.e., social and family status) is discarded in favor of a new role that goes beyond the individual. This role is considered unique, professional, and assigned for the length of the mission (Weiss, 2005). Each individual is considered a unit in relation to their environment (Ittelson, 1973). This underpins the existence of a consubstantial individual-environment link. These constitute two elements of the same system, with each element's characteristics inextricably linked to those of the other and the system as a whole. This, ultimately, cannot be separated from the stress response. The primary function of the stress response is to cope with environmental challenges. Operational constraints in such environments impose a combination of chronic and acute stressors on the mission. A certain degree of stress is considered necessary for adaptation both biologically (Seyle, 1950) and psychologically (Lazarus and Folkman, 1984). Eustress, or positive stress (Seyle, 1974), can improve adaptive responses in extreme environments (Palinkas, 1992). However, distress in these environments can generate dysfunctional adaptation (Geuna et al., 1995; Nicolas and Weiss, 2009).

Data from historical and analogous space flights, such as research stations in Antarctica, and the International Space Station (ISS), suggest that prolonged periods of social and sensory monotony can have a negative impact on human psychosocial health (Brown, 1961; Heron, 1961). Many studies have shown that disorders, such as somatic symptoms (e.g., fatigue, headaches, weight gain, gastrointestinal complaints, rheumatic aches, and pains), sleep disorders (e.g., difficulty falling asleep or staying asleep, changes in circadian rhythms), mood disorders (e.g., anger, irritability, anxiety), psychiatric disorders (e.g., depression, personality), and increased tension and conflict between crew members or with people outside the group are prevalent in confined environments (Palinkas et al., 2004a; Palinkas and Suedfeld, 2008; Shea et al., 2011; Kanas et al., 2013; Basner et al., 2014). Cognitive problems have also been reported, such as a decrease in precision and short-term memory, increased reaction time, difficulty concentrating, suggestion sensitivity, intellectual inertia, and a disturbance of vigilance (Palinkas et al., 1995; Shea et al., 2011). Nevertheless, the results reported by the literature on cognitive performance are inconclusive (Strangman et al., 2014; Pagel and Choukèr, 2016). Liu et al. (2016) also showed that isolation and confinement resulted in a decreased ability to regulate emotions in addition to an increased vulnerability to negative emotions. Rohrer's (1961) three-step adaptive phase model considers the effects of isolation and confinement in extreme environments on crew members' emotions, performance, and interpersonal relationships. It shows a rise in anxiety and nervousness, followed by an increase in depression due to a monotonous daily life, and finally the appearance of obvious hostility. However, emotions, whether negative or positive, are necessary for the adaptation of human beings to their environment. Therefore, it could be relevant to import Barbara Fredrickson's (1998) broaden-and-build theory of positive emotions into these environments. The effects of positive emotions have been demonstrated on different types of variables, such as health, longevity, relationship quality, or performance (Lyubomirsky et al., 2005; Lester et al., 2021). Consequently, the optimization of adaptation in these environments may be achieved through the stimulation of positive emotions and awareness of their occurrence. The question then arises as to how to stimulate them. What is the environment itself? What are the human being's own characteristics? What can be trained, and how? In what type of living environment?

Overall, the literature suggests that the operational constraints of ICE and/or EUE pose a challenge to the adaptability of the personnel, who are immersed in an artificial, stressful environment. This is particularly inherent to environmental, inter-/ intrapersonal, individual and technical factors. The meditative literature meeting this challenge requires an efficient body-brain connection, which is the individual's ability to pay attention to information from the body that emerges through non-judgmental, focused attention in the present moment to the unfolding experience (Kabat-Zinn, 1994) and to notice subtle changes that are consistent with the available environmental information (Mehling et al., 2009). Therefore, body awareness can be a determining factor in an individual's ability to adapt to this type of environment in the long term, especially in the perspective of missions exceeding 2 months of confinement and likely more in the future.

2. Sensory signal interaction

« Man is a unit » (Caston, 1993). This unit includes a body and a psyche. The concept of « body » is still extremely difficult to define because it belongs to a polysemous semantic Universe. « Body image » defines the conscious representation we have of our body in its static or dynamic state. It is based on the interoceptive sensory data (visceral), the proprioceptive (muscles, joints), and the exteroceptive (surface). It has an emotional component. This image is constantly revised according to lived experiences, but the whole body is fully felt at the end of childhood. The body schema is a structure that integrates perception and integration of sensory information.

Exteroceptive body awareness refers to the implicit knowledge we have of our body in relation to space and movement. It results from the integration of multimodal exteroceptive signals (e.g., vision, sound, touch), vestibular, and proprioceptive systems, and voluntary motor systems.

Interoception refers to the perception of the physiological condition of the body, including hunger, temperature, and heart rate. This internal perception of the body contributes to the regulation of physiological integrity (homeostasis) (Craig, 2002; 2003; 2009). Enhanced interoception is related to non-judgmental acceptance of bodily sensations and a sense of self grounded in experiencing physical sensations in the present moment (Mehling et al., 2009). There is a growing appreciation that interoception is integral to higher-order cognition, such as emotional memory (Pollatos and Schandry, 2008), learning, and decision-making (Werner et al., 2009), and consciousness.

Generally, interoceptive sensations are located more diffusely compared to exteroceptive sensations. In some cases, interoceptive information is overshadowed by, or inseparable from, exteroceptive cues; for example, sensations of respiration from chest wall muscle proprioceptors and upper airway somatosensation lie in the perceptual foreground relative to interoceptive signals from alveolar tissue or blood gases. In some motivationally relevant states, interoceptive information is amplified or overtaken by the recruitment of exteroceptive pathways, as with the pain felt in the chest wall and upper arm during cardiac ischemia.

Then, exteroceptive, and interoceptive signals interact in the sense of self (Suzuki et al., 2013) and participate in affective feelings, drives, and emotions (Craig, 2009; Crichtley and Harrison, 2013; Valenzuela-Moguillansky et al., 2017).

It is little explored in healthy stress whether sensory integration is actively involved in the adaptive response of subjects experiencing physical environmental constraints as psychic (Levit-Binun and Golland, 2012), even though several theoretical, and experimental arguments emphasize its role in emotional, mental (Morrison et al., 2013), thymic (Balaban, 2002; Engel-Yeger and Dunn, 2011), attention (Delevoye-Turrell and Bobineau, 2012; Morrison et al., 2013), cognitive (Ashendorf et al., 2009) and social functioning (Centelles, 2009).

If sensory deprivation is an experimental paradigm, there are professional environments immersing individuals in very different sensory environments in living settings, either because of inadequate sensory stimulation, a lack of variation in these stimulations, or an over-stimulation of a sensory modality. These professional environments characterize most ICE/EUE. In sum, the presence of alterations in exteroceptive signals may interact with interoceptive processes and the neural circuitry that supports interoceptive awareness. This suggests that a healthy subject living and working in a non-ecological environment, such as one of the three analogs (SSBN, Antarctica and sub-Antarctica bases, and spatial bases), may integrate interoceptive and exteroceptive cues differently when compared with sensory integration in their usual ecological environment.

The literature on ICE/EUE describes a link between changes in sensory stimuli in the living environment and changes in emotional and mood disorders (Palinkas et al., 2007; Brasher et al., 2010), attentional, and cognitive (Palinkas et al., 1996; Joly, 2009) and social (Palinkas et al., 2004b) underlying maladaptive stress responses (Joly, 2009; Crosnier, 2013). These disorders appear during the missions in individuals without any malfunction of the sense of touch. All these data suggest that sensory immersion in these environments may have deleterious effects on physical, mental, and cognitive health through mechanisms affecting sensory integration.

3. Benefits of mindfulness on adaptation

Adaptation emerges from the elaboration of interoceptive information and its integration with exteroceptive signals (Crichtley and Harrison, 2013). Adaptive behavior is motivated by the need to ensure the immediate and prospective integrity of internal physiology, from which emerge motivational states and emotions of increasing complexity. The integration of rich humoral and neural viscerosensory information is supported by a relatively small set of interacting brain areas linked to low-level homeostatic reflexes; however, these areas can draw on both instinctive and volitional behavioral repertoires, when functionally challenged, specifically in terms of allostasis (Sterling, 2012). Comprehending and studying exteroceptive and interoceptive integration has paramount value. Correct access to interoceptive information is key to allostasis and adaptive regulation of the organism, whereas alterations in interoceptive processing appear to be associated with various conditions.

Adaptive regulation of the organism faced with a stressful environment has been highlighted for individuals characterized by a high level of the so-called Mindfulness Disposition (MD). MD refers to the awareness that emerges from paying intentional, present-moment, non-judgmental attention to an unfolding experience moment by moment (Kabat-Zinn, 1994). MD has been conceptualized as a trait (Brown and Ryan, 2003; Grossman et al., 2004), i.e., the ability to be mindful in everyday life, regardless of events, and consistently over time (Kilpatrick et al., 2011). MD is associated with various positive physical and psychological health factors (Brown and Ryan, 2003), such as efficient emotional and stress regulation (Chiesa and Serretti, 2009). These subjects are described as resilient individuals through deliberate and non-judgmental attentiveness to present-moment body sensations, leading to the transient nature of negative effects (Kabat-Zinn, 1994). Strong associations between MD and positive psychological outcomes emphasize mindfulness as an « optimizing agent » (Phan et al., 2020) that could be incorporated into the positive psychology framework (Seligman and Csikszentmihalyi, 2000). Positive psychology as a discipline has produced useful research findings that can offer insights into the psychological factors that promote human flourishing in people's personal lives and the workplace but also in organizational and training settings (Seligman and Csikszentmihalyi, 2000; Cameron et al., 2003). The intricate association between mindfulness and positive psychology could be understood by looking at the two dimensions of mindfulness: acceptance and presence (Kabat-Zinn, 1994; Walach et al., 2006). Acceptance consists of recognizing inner events such as emotions, thoughts, or beliefs when one feels them (Hayes et al., 2004). Acceptance does not imply resignation, but rather perceiving one's own experience through an attitude of acknowledging it rather than judging it as either good or bad. Presence is the feeling of being in the moment; it refers to the degree to which a subject is grounded in awareness itself. Empirical research has mainly operationalised mindfulness as the product of a single factor: presence. However, further elucidation of the differential roles of presence and acceptance for individuals' attitudinal and behavioural outcomes would help to unravel the processes by which mindfulness impacts individuals' health, well-being and behaviour (Kohls et al., 2009; Liang et al., 2018).

Mindfulness techniques are recognized as being useful for facilitating the development of the MD and associated abilities to help subjects deal with their daily stressors and alleviate their consequences on health and wellbeing in terms of attitudinal and behavioral outcomes. Training programs have been shown to develop the state of mindfulness (Bartlett et al., 2019), but they may also positively impact the MD by activating the corresponding trait (Kiken et al., 2015). Mindfulness-Based Stress Reduction (MBSR; Kabat-Zinn et al., 1985) is the most widely used and validated protocol for healthy subjects. The MBSR is an 8-week program in which participants meet for a 2-h (or two-and-a-half-hour) session every week and are asked to perform formal practices for 45 min per day, 6 days per week, in addition to informal practices such as mindful eating and mindful walking. ACT (Acceptance Commitment Therapy; Flaxman and Bond, 2006; Hayes and Feldman, 2004) can also be used to develop the acceptance dimension by emphasizing the development of the ability to focus on one's own experience. The effectiveness of such a program depends on several factors, among them the frequency of practice throughout and after the program (e.g., Carson et al., 2004). Being self-disciplined in performing their daily practices is crucial to being able to integrate mindfulness into everyday life activities and interactions.

The mindfulness function would enact its effects on emotion and stress management through plastic changes in mental and brain functions related to attention regulation, body awareness, emotion regulation, and self-perspectives (Hölzel et al., 2011; Verdonk et al., 2020). The focus on body awareness in mindfulness definitions suggests that an individual's sensory processing pattern may influence their mindfulness abilities (Hebert, 2016). Recent studies highlight the role of interoception processes in the higher body awareness associated with MD (Guendelman et al., 2017; Hanley et al., 2017). Furthermore, strong links between MD and interoceptive awareness have also been discovered (Hanley et al., 2017).

The aim of this paper is therefore to review mindfulness functioning as a characteristic of the individual that is conducive to sustainable adaptation in ICE/EUE environments, in addition to the proposed new technologies to improve mindfulness functioning itself. Faced with the lack of substantial literature focusing on the application of mindfulness in space (Pagnini et al., 2019), most of the studies are based on mindfulness experiences from analog environments and military contexts, in addition to other studies on challenging conditions.

4. Research of mindfulness in space analogs

Professional ICE and EUE environments are often called « analogs » because they are characterized by similarities with spatial environments. EUE are linked to the hazards that characterize them (nuclear submarine, Antarctic research base, spacecraft). They are usually associated with ICE because these environments (commercial fishing boats, mining camps, and prisons) are unusual for most human beings. However, depending on the degree to which environments are characterized as ICE and/or EUE, they can be so different that their comparison tends to be reconsidered (Suedfeld et al., 2018).

4.1. Mindfulness functioning in atypical environments

One of these specific ICE environments is the Sub-Surface Ballistic Missile Nuclear Submarine (SSBN). This is a professional environment in which personnel are both isolated and confined during patrols that can last longer than 2months. This environment is known to degrade submariners' mood, cognition, and sensoriality (Joly, 2009; Crosnier, 2013; Lafontaine, 2019; Ferragu, 2020). An exploratory empirical study followed a cohort of 24 volunteer submariners (Aufauvre-Poupon et al., 2021). MD was assessed with the Freiburg Mindfulness Inventory (FMI; Trousselard et al., 2010) in order to identify two groups (mindful and non-mindful) using a PCA with a k-means and compare changes in subjective emotional state, interoception, and health-related behaviors (sleep and food intake) during the patrol. MD and interoception were collected in four sessions: before the patrol (baseline), twice during the patrol on days 25 (D25) and 55 (D55), and once after the end of the patrol (recovery). Health-related behaviors (sleep and food intake) were only evaluated twice (at baseline and recovery).

Overall, the results showed that MD remained stable during the patrol, especially in the acceptance dimension. The presence dimension tended to decrease in the mindful group but not in the non-mindful group. Psychological health deteriorated during the patrol. Mindful submariners demonstrated better positive emotions, psychological adaptation, and interoception than the non-mindful group. The mindful group also demonstrated better subjective health behaviors (sleeping and eating) than the non-mindful group.

Raft survival missions comprise a particular EUE environment. This is an extreme professional environment that may be tried when serious boat damage occurs. To study the impact of such an EUE, 12 student sailors volunteered to experiment with survival in a life raft (Trousselard, 2018). The life raft was anchored in open waters, with the subjects in autonomous survival mode. The international regulations in effect for the approval of life rafts defined the survival conditions of hydration and food as 50 cc of water per day and a food bar of approximately 1,000 kcal per day, with a minimum autonomy of 5 days. MD was assessed using the FMI to identify two groups (mindful and non-mindful) based on the median of the total group. Changes in emotional subjective states, interoception, and objective exteroception performances were compared between groups. Variables were recorded immediately before and immediately after the survival mission.

The main purpose of this study was to evaluate the impact of a 5-day raft survival mission on sensory perception (external sensors) and psychophysiological functioning according to MD.

Overall, the results showed that psychological states deteriorated during the survival experience. Mindful student sailors demonstrated better positive emotional states with a lower level of negative emotion and a higher level of positive emotion. Furthermore, mindful student sailors demonstrated lower declines in taste and olfactory performances than the non-mindful group. Recovery was not assessed.

No further studies have been found on mindfulness functioning in the literature in ICE/EUE environments.

Mindfulness functioning has also been investigated in the context of military operations. A study examined the psychophysiological and cognitive responses induced by military training for escaping to a submarine simulator according to the submariners' mindfulness level (Trousselard, 2009). A total of 13 male submariners were recruited. MD was assessed using the FMI to identify two groups (the FMI + group and the FMI-group) based on the mean mindfulness score found in the submariner population. Submariners were compared on sympathovagal balance, salivary cortisol, mood, and sleep perception. Short-term memory was assessed using the 10-min Digit Span test, while declarative memory was measured using a set of 12 pictures. Data were collected before the post (baseline), immediately after the post (post), and 2 hours after it (recovery). Overall, submariners with higher mindfulness scores exhibited lower stress reactions as measured by cortisol concentration and LF/HF ratio, lower latency to go to sleep, better sleep quality after the simulation, and less cognitive degradation (i.e., better recall for declarative memory) at all three-time points. The cognitive degradation was concomitant with elevated salivary cortisol levels. Thus, psychophysiological and cognitive changes induced by military exercises appeared to be influenced by the subject's mindfulness level.

Another study has explored the psychological skills used by elite military pilots to improve performance in high-demand maneuvers (Hohmann and Orlick, 2014). Semi-structured interviews were conducted on 15 elite Canadian pilots over a period of 4 days and prepared according to the time before and in-between flights (pre-flight), during flight (mission execution), and between the end of a flight and the preparation for the next one (post-flight). The pilots did not express anxiety or even fear during daily routines, nor did they use regular check procedures, visualization, positive thinking, or breathing techniques to manage stress. In flight, they entered a state of flow. Being in the present appears to be an important component to deal with environmental demands.

They expressed a high level of situational awareness linked to prior experience. They remained focused, constantly analyzing their decision-making, when faced with critical situations. When distracted, they used adaptative strategies to avoid shifting (e.g., verbal cues are the most commonly used for prioritizing tasks). They accepted responsibility for their errors and searched for constant improvement.

Mindfulness functioning has been involved in weight loss (Mantzios et al., 2015). The weight of 97 military recruits was measured on the first day of training (baseline) and 5 weeks later (after). Mindfulness functioning was assessed using the Mindful Attention and Awareness Scale (Brown and Ryan, 2003). The level of self-compassion was also collected. Results highlighted the fact that 43 participants gained weight while 54 lost weight. Weight loss has been linked to better mindfulness functioning and self-compassion. Weight gain, on the other hand, has been associated with negative thoughts and intolerance for uncertainty.

There are numerous articles on mindfulness programs to help military personnel manage stress and health while on missions. Nevertheless, few articles focus on the impact of mindfulness readiness as a factor in mission adaptation. Furthermore, these articles focus primarily on soldiers, less on Navy personnel, and even less on submariners. Within the frameworks of Barbara Fredrickson's (1998) broaden-and-build theory of positive emotions, these findings suggest that MD may be a relevant function to support adaptation and mental toughness over time in the ICE/EUE population.

4.2. Potential of new technologies to train mindfulness in extreme situations

Practices that develop an individual's capacity to be mindful have been individualized as intervention programs with different formulations and distinct goals. These include « mindfulness-based stress reduction » (MBSR) (Kabat-Zinn, 1982), which was the first program used in the management of chronic pain and then depression, « Mindfulness-Based Cognitive Therapy » (MBCT) (Segal et al., 2002), « Dialectical Behavior Therapy » (DBT) (Linehan, 1993), and « Acceptance and Commitment Therapy » (ACT) (Hayes et al., 1999). In addition, the Vittoz method, developed in 1925, is a five-sense-based technique to reduce maladaptive automatic responses and improve attention to the present moment (Shankland et al., 2021). Whether for MBSR or other mindfulness interventions, maintaining, let alone improving, mindfulness levels requires a regular, daily practice of the exercises taught (Carmody & Baer, 2008). The majority of mindfulness programs exhibit positive outcomes, such as effectiveness in reducing psychological symptoms and thus improving overall health (Grossman et al., 2004; Carmody et al., 2009; Irving et al., 2009; Gu et al., 2015). The Langerian cognitive construct is the process of intentionally paying attention to the present moment, being aware of novelty in experiences or situations, and perceiving differences between contexts and events (Langer, 1989). These focus on improving openness, flexibility, and attentiveness to new situations, resulting in greater adaptability, engagement, creativity, and innovation (Langer and Moldoveanu, 2000; Pagnini et al., 2016). This training results in a higher quality of life and lower levels of negative emotions, anxiety, and depressive symptoms (Pagnini et al., 2022).

No research has been conducted about mindfulness training programs in space and analog environments. The majority of mindfulness-based interventions in this context focus on the military context, notably on caring for soldiers who have developed a posttraumatic stress disorder (King et al., 2013; Vujanovic et al., 2013; Brewer, 2014; Nassif et al., 2019). Mindfulness-based interventions appear relevant to deal with stress management in the theater of combat operations (Seppälä et al., 2014; Barnes et al., 2016).

An MBSR intervention was conducted on 16 military pilots for 1 year (Meland et al., 2015). MD, anxiety, and self-perceived mental skills were evaluated before and after the intervention. Interviews were also performed at the end, and MD was assessed for 2 years. Results showed a decrease in somatic anxiety related to performance. Moreover, mindfulness, attention regulation, and arousal regulation improved. Mindfulness functioning remained high at follow-up. Nevertheless, this study has indicated that the mindfulness intervention is time-consuming and may impact the expected benefits. Frustration is one of the consequences induced by the lack of immediate results. The soldiers reported that being more mindful had physical, psychological, and interpersonal benefits.

Mindfulness-based Mind Fitness Training (MMFT) was developed to improve adaptation to stressors and resilience in pre-deployment military personnel. This training aimed to cultivate interoceptive awareness, attentional control, and tolerance to the present moment in a highly situational environment. A total of 34 Marines received an MMFT intervention prior to deployment (Stanley et al., 2011). Self-reported mindfulness and perceived stress were assessed before and after the operational mission. Results show that the time allocated to practice is correlated to the level of mindfulness. Moreover, this study highlights that the practice tends to decrease while environmental stressors increase. This point is particularly important regarding future long-term space missions. It appears that motivation is a significant predictor of the time dedicated to practice. Furthermore, a high level of mindfulness was associated with less subjective stress. Johnson et al. (2014) conducted a study on eight Marines who received an MMFT intervention during 8 weeks of individual practice prior to deployment. Heart rate, breathing rate, plasma neuropeptide Y concentration, perceived stress, and brain activation were evaluated. Overall, results reported a greater heart rate reactivity and a better recovery for those who received the MMFT compared to the control group. Moreover, their heart rate and concentration of plasma neuropeptide Y decreased. Also, the right insula and the anterior cingulate cortex were less active in response to emotional facial expressions. The breathing rate was lower for the group that only received the MMFT training during the recovery. Thus, this intervention appears to enhance the performance, resilience, and efficiency of soldiers in high-stress situations, while also improving their recovery time after the mission. These results were corroborated by Jha et al. (2017), who investigated the impact of MMF interventions on performance in Marines prior to deployment. Attentional performance increased and self-reported mind wandering decreased in the MMFT group compared to the control group. These measurements also correlated with the time allocated to practice. Thus, MMFT interventions may also protect against attentional lapses in high-demand situations. These effects were more pronounced in soldiers who performed practice-focused interventions instead of didactic-focused interventions (Jha et al., 2015). Jha et al. (2020) found in an 80-soldier cohort that MMFT interventions protect against cognitive decline, as assessed by working memory and sustained attention tasks, compared to controls. Thus, it appears to be a relevant tool to preserve cognitive functioning in a high-demand situation.

Recently, Nassif et al. (2022) conducted two studies on infantry battalion soldiers. This study aimed to investigate the impact of Mindfulness-Based Attention Training (MBAT) on performance, mental skills, and psychological state. Each soldier was allocated to one of the three MBAT conditions: proctored practice, unproctored practice, or waitlist control. The intervention took place for 2 hours per week for 4 weeks. Individual proctored (i.e., supervised session) or unproctored (i.e., autonomous session) practice took up an additional 4 weeks. The MBAT intervention improved the soldiers' performance and mental skills compared to the control group. The results showed an increase in performance under physical stress, emotion regulation, mental toughness, and self-reported awareness, and a reduction in attention loss that was proportional to the amount of time spent practicing.

5. Discussion

This brief review shows that few studies have been conducted on mindfulness functioning in ICE/EUE environments. They mainly focused on the individual in space analogs, especially military environments (Pagnini et al., 2019). The results taken as a whole underline the importance of better understanding the relationship between the body and the environment in space missions characterized by ICE/EUE constraints. They will allow us to consider the next regular and long-distance space travels that will take place and that will be available to a significant portion of the population. We are on the cusp of long-distance space journeys that will push our limits even further (Tafforin, 2022). In this context, it is more than necessary to implement solutions that limit the loss of homeostasis between the demands of the environment and the resources that an individual can mobilize. This state of equilibrium in the individual-environment system is specific to each person and depends on their perception of the world. This state is essential for keeping these entities in optimal operational conditions and promoting their wellbeing. It is at this stage that a quality adaptation may take place over time. This is the challenge of the next space missions. They will not be limited to 6 months, as is currently the case on the International Space Station (ISS), but could last a lifetime.

Thus, the results of the exploratory studies in ICE/EUE environments may suggest two different but complementary countermeasures.

The first one will focus on how to choose the best sensory environment for long space missions. Experts in habitability design must develop products, systems, and architecture for space. Knowledge of the impact of non-ecological sensory cues, in other words, or the unusual sensory inputs that ICE and EUE can induce, on adaptability can help define the optimal environment for solving the unique challenges of living and working in extreme environments. An illustration of this important parameter can be seen, for example, in the design of the SpaceX Crew Dragon cabin, launched in April 2021. The entire cabin, and particularly the seats, have been significantly improved. Furthermore, a recent study has linked positive psychology constructs to the physically built workplace environment using the concept of the Positive Built Workplace Environment (PBWE; Grant et al., 2019). It explored the links between the physical attributes of well-designed, sustainable contemporary workspaces, performance, and wellbeing, and the humanistic values central to the positive organizational enterprise. It would be pertinent to explore how the physical attributes of different space stations, as analogs, interact with the lived experiences of individuals who work in stations and to consider the best physical attributes that stimulate and support innovative, agile, and collaborative work in spite of the environmental constraints that ICEs require. Specifically, for ICE, designing for a sensory-rich life and work environment appears particularly relevant. This would be helpful for experiencing all senses during the missions.

The second one will focus on mindfulness functioning. Meditation and mindfulness, in addition to other physical activities that involve the motor component with attentional awareness of sensory functioning, are practices that can modify sensorimotor processing (Kerr et al., 2016) and foster non-judgmental connections with emotions and bodily sensations (Gard et al., 2014). Concerning mindfulness-based positive psychology (Allen et al., 2021), a few of the mindfulness-based interventions show powerful efficacy as they could enhance specific positive variables. Further studies are needed to develop the existing interventions and incorporate facilities to enhance positive outcomes. Furthermore, as a mindfulness program is all the more effective when the practice is regular, it could be pertinent to emphasize programs that reinforce daily practices. Among the existing methods for developing mindful awareness through informal/ integrated practices, the Vittoz method may correspond to an integrated practice that should help enhance mindfulness in daily life (Shankland et al., 2021). It focuses on training self-regulation through present-moment attention practices using applications mainly based on the five senses and acting with awareness (e.g., talking, shaking hands with colleagues, and listening to sounds; Mingant, 2007). These are considered to be brief and informal mindfulness practices, as opposed to those planned for a specific time and place (e.g., on a cushion in a peaceful room). As for the formal and informal practices of physical activity that lead a person to have an athletic practice (e.g., walking to work instead of training twice a week at the gym), it may be salient to list what astronauts' daily activities could be easily implemented as informal mindfulness daily practices. This could help re-establish coherent exteroceptive body awareness and reacquaint subjects with bodily sensations as part of their embodied subjectivity. In turn, coherent exteroceptive body awareness would improve the subjects' agility and self-confidence, while a connection with bodily sensations would provide tools for emotional regulation, also improving self-confidence. Altogether, this would increase functionality while decreasing depression and anxiety and improving the quality of life during long-term space missions.

These two applied approaches, one based on environmental stimulation and the other on individual functioning, support the idea that targeting both exteroceptive and interoceptive body awareness may be synergistic, enhancing the benefits of both dimensions of countermeasures. These two proposals are part of a positive psychology approach (i.e., salutogenic or health-producing) that has been adapted to ICEs and their analogs, but also to space vehicles (Suedfeld, 2001). Maintaining a positive salutogenic functioning is helpful for dealing with stress (Palinkas et al., 1995; Ritsher et al., 2005; Ihle et al., 2006). The question of how to use positive psychology to guard against the difficulties and dangers of space travel and missions is crucial. At the same time, personnel should also be trained to accept negative moods and experiences during the mission, which will be inevitable. This is a specific objective of mindfulness-based interventions. Taken together, the evidence shows that there is a pressing need to develop and validate a mindfulness-based intervention that integrates positive psychology for the education, training, and support of future space crewmembers.

Furthermore, maintaining an ecological environment for assessing sensory integration and testing body awareness is an experimental challenge. A technological solution created to overcome such an ordeal would be an immersive media using virtual reality and/or augmented reality. It may be useful to measure the disruptive effects of prolonged exposure to confined environments. Aside from assessment, virtual reality has been used to treat anxiety disorders in various settings (Valmaggia et al., 2016). It could represent an innovative tool for mitigating, if not correcting, the impairment of the perception of sensory signals. Despite the fact that immersive reality includes an experimental platform that can induce virtual illusions with a partially reproduced sensory environment and a limited gamut of stimulation when compared to well-ordered, complete, and consistent physical reality, past studies have demonstrated that the participants exposed to virtual reality were able to transfer their newly gained skills into reality (Malbos et al., 2013). This generalization is noteworthy as the everyday perception of physical reality relies on a low-level, continuous calibration of raw data from biological sensors, which might be thought of as mild, continuous hallucinations or imperfect implicit neural hypotheses of what to expect from the real world. These are constantly corrected based on new input to enhance the perceived veracity of a virtual world. Such references to the real world would change during an ICE/EUE mission, and even more so during extended space missions. Consequently, data on sensory integration in ICE/EUE are needed for developing the best implementation in terms of sensory virtual signals and body awareness exercises.

Moreover, recent studies have demonstrated the potential of vagus nerve stimulation in many clinical areas, either to reduce symptoms or to improve recovery. Pathologies studied are associated with psychological and sleep disorders (e.g., depression, anxiety, post-traumatic stress disorder), developmental (e.g., psychomotor impairment), and somatic neurological issues (e.g., epilepsy, Parkinson's disease), metabolic (diabetes), in addition to cardiovascular and gastrointestinal conditions (e.g., IBD) or chronic pain or tinnitus (Kong et al., 2018; Zhao et al., 2020; Ridgewell et al., 2021; Wang et al., 2022). Moreover, cognitive benefits have been observed in healthy subjects under stress constraints (D'Agostini et al., 2021). Gerritsen and Band (2018) demonstrated a causal link between vagus nerve stimulation, breathing techniques, and positive outcomes. They described a neuropsychological model in which breathing techniques stimulate the vagus nerve, resulting in an increase in parasympathetic activity over sympathetic activity, which improves health and cognitive performance.

Mindfulness functioning promotes interoceptive awareness by improving self-awareness and regulating responses induced by the body-brain axis. A Neurofeedback-Augmented Mindfulness Training Task (NAMT) has been used on adolescents to investigate the role of the insular cortex in mindfulness interventions. It consists of mindfulness training followed by eight neuroimaging tasks in which subjects are assigned one of two conditions: a focus on breath (active neurofeedback) or a described condition (control).

The active condition was found to increase the activity of the anterior insular cortex and decrease the activity of the mid and posterior insular cortex during the neurofeedback tasks (Yu et al., 2022). Activities of the anterior and posterior insular cortex were associated with lower self-reported life satisfaction and less pain behavior. NAMT appears to be useful for inducing brain activations with positive health outcomes. Other technologies may have positive potential for health in stressful environments. There are those based on artificial sensation using direct stimulation of interoceptive signals, interoceptive illusion using an external environment to modify interoception, emotional augmentation, and entrainment (Schoeller et al., 2023).

While the limited amount of data appears to support the idea that mindfulness, as a function developed naturally or through a specific mindfulness program training, is associated with stress reduction and higher performance in an ICE/EUE environment, the number of sources is limited, and few studies are adequately powered to directly test this hypothesis. Such studies have been conducted only on military personnel before, during, and after combat, limiting the generalizability of the results. Furthermore, there is a lack of substantial literature focused on the application of mindfulness interventions in space. Mindfulness interventions have the potential to increase adaptation and go further into the challenging conditions of future long-term space missions. Thus, mindfulness-based interventions will increase psychological resources, decrease functional stress, and increase cognitive outcomes and operational proficiency. Nevertheless, the time dedicated to practice will increase the results' outcomes. In conjunction with the development of new technologies, mindfulness-based interventions may reduce the environmental demand inherent in future space missions (e.g., separation from loved ones, isolation, confinement, lack of sleep, and social constraints) and improve performance. This element will be very important for future perspectives, decreasing both physiological activation and worrying thoughts about the mission. Moreover, mindfulness interventions will need to take astronaut workload into account. The time spent on programs should be kept to a minimum. Another concern is about the adherence of this population to this type of intervention. Demystifying the real benefits highlighted in the literature seems to be a prerequisite for mindfulness-based programs being used to their full potential. To this aim, new technologies may also help to develop mindfulness and have regular practice during the mission. The authors noted that mindfulness interventions require some training and practice before the expected benefits are observed. Frustration is one of the consequences induced by the lack of immediate results (Stanley et al., 2011; Meland et al., 2015). On the other hand, it is clear that there has been little empirical work testing the effects of mindfulness training on group cohesion and group functioning. The social point of view needs to be studied further. The purpose is to evaluate whether the value of strengthening the mindfulness of individuals is relevant to optimizing the functioning of the group. Parsons et al. (2006) examined the impact of mindfulness interventions (i.e., one-day short and seven-day long training conditions) on decision-making. Decision-making was evaluated using the NASA Moon Survival Task (Hall and Watson, 1970), which aims to measure problem-solving during a complex strategy task. The task was repeated twice in order to assess the performance of 332 individuals and then in groups of three. The mindfulness intervention consisted of a body scan program. Subjects completed mindfulness (Mindfulness Attention and Awareness Scale, Five Facet Mindfulness Questionnaire) and neuroticism trait (Big Five Inventory) questionnaires. Even if the results did not reach significance, it seems that the length of mindfulness training tends to impact group performance. Any findings were reported for the individual's performance. The authors concluded that even one session of mindfulness training can induce benefits both for the individual and the group in decision-making performance. Nevertheless, they pointed out that the body scan program may not benefit the training group's decision-making. Another study by Cleirigh and Greaney (2015) investigated the effect of mindfulness-based interventions on a group decision-making task. The intervention was inspired by mindfulness-based cognitive therapy. Participants completed mindfulness questionnaires (Mindfulness Toronto Scale, Mindfulness Attitudes Scale), cohesion group questionnaires, and performed the Winter Survival Task (Johnson and Johnson, 1991) in groups of four. Their results highlighted that a 10-min intervention induced positive outcomes on group performance and cohesion when compared to controls.

6. Conclusion

Being mindful seems to be an essential component in maintaining performance and preserving positive outcomes in ICE/EUE. Nevertheless, we lack data in these environments. It is important to explore how this may be accomplished using new technologies to enrich existing practices. There is a need to better understand the links between body perception quality and subject adaptation to the spatial environment. It involves studying the missions in ICE and EUE in terms of duration, a disruption in the quality of sensory signal perception, and body awareness emerging as a certain level of time constraints that may affect the general efficiency of the crew during their ongoing mission. Although nuclear submarines, Antarctica, and sub-Antarctica bases are being studied as similar environments to better predict human adaptation to long space missions to the ISS, Mars, and 1 day into our solar system, extrapolating the results about sensory integration on adaptation from these two analogs without taking the limitations of the comparisons into account is highly risky. Multi-chamber facilities and CELSS could be relevant candidates for evaluating the different countermeasures that focus on the mind-body connection in anticipation of his long-term missions. Furthermore, there is a need to better understand the role of dispositional inter-subject differences in non-ecological exteroceptive environment adaptation to prepare more effectively for long space missions, including long space travel. Findings from these first studies suggest that mindfulness functioning appears to protect against the negative effects of long-term confinement in an extreme environment. They are the first steps in the development of a number of relevant countermeasures to improve the wellbeing and operational capacity of submariners and polar winterers, and then astronauts in future long space missions. Beyond that, these results lead us to think about mindfulness programs adapted to the constraints of space missions for both the individual and the group's physical, cognitive, and mental health.

7. References

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Synthèse des résultats principaux

L'étude PRESENCE avait pour objectifs : (1) conduire une réflexion qui examine le fonctionnement de la MD comme une caractéristique de l'individu propice à l'émergence d'une adaptation durable en ICE/EUE ; et (2) cibler les nouvelles technologies qui améliorent le fonctionnement de la MD.

Malgré des bénéfices positifs pour la santé, une réduction de l'état de stress et de meilleures performances du fonctionnement mindful décrits dans la littérature, peu d'études ont en exploré l'intérêt de ce fonctionnement dans les environnements ICE/EUE, et encore moins pour les LDSE. Nos résultats soulignent le faible nombre de sources disponibles dans la littérature. Pour autant, l'analyse des données disponibles permet de proposer deux types de mesures pour améliorer la synergie des informations intéro- et extéroceptives. La première se réfère à l'appauvrissement sensoriel extéroceptif des environnements qui pourrait avoir un impact réduit du fait de l'amélioration de la conscience intéro- et extéroceptive associée au fonctionnement mindful (Aufauvre-Poupon et al., 2021 ; Verdonk et al., 2021). La deuxième se réfère au fonctionnement individuel en ciblant la pratique d'interventions permettant de favoriser la communication de l'axe corps-cerveau pour renforcer le fonctionnement *mindfulness*. De plus, nos résultats montrent que les nouvelles technologies pourraient permettre d'enrichir les pratiques existantes, et de soutenir une pratique plus régulière dans le temps. Une pratique régulière d'exercice renforçant le fonctionnement mindful est un enjeu pour l'efficacité des contremesures dans ce champ. Ainsi, le renforcement et le maintien du fonctionnement mindful des astronautes permettraient une réponse au stress plus adaptée dans la durée soulignant son intérêt pour la réussite des missions LDSE.

Plus récemment, la littérature a révélé l'implication des signaux intéroceptifs dans l'émergence de la conscience de soi, celle-ci impliquant la perception des changements corporels en réponse aux stimulations venant de l'extérieur. L'intégration multisensorielle des signaux aussi bien intéro- que extéroceptifs permet de façonner et de maintenir la conscience de soi corporelle (i.e., structure intégrative qui organise et coordonne les fonctions affectives, cognitives, sensorimotrices et végétatives). Elle génère ainsi une représentation du monde composée de signaux provenant de l'état interne du corps, et de la position du corps dans l'espace. Moseley et al. (2012) ont proposé un modèle théorique de l'intégration des signaux intéro- et extéroceptifs à travers l'existence d'une *body matrix* (i.e., représentation multisensorielle du corps et de l'espace directement autour du corps par le cerveau). Le corps, est vu ici comme un système. La *body matrix* serait composée par un ensemble de structures neuronales, impliquant le cortex pariétal supérieur, le cortex cingulaire antérieur et postérieur, l'insula avec une superposition dans le sillon intrapariétal. Cette *body matrix* permettrait de maintenir l'homéostasie et favoriser l'adaptation aux changements de la structure et de l'orientation du corps. Les théories bayésiennes se sont attachées à comprendre les processus intéroceptifs à l'œuvre dans les modèles de codage prédictifs impliqués dans le fonctionnement de la *body matrix* (Petzschner et al., 2021). Ces dernières suggèrent que le sentiment de présence intervient dès lors que des signaux prédictifs intéroceptifs sont correctement associés aux entrées sensorielles afin de réduire au minimum les erreurs de prédiction. Le CNS participe à former cette représentation du monde qu'elle soit implicite ou explicite en mobilisant des boucles de contrôle sensoriel pouvant intervenir selon trois stades : (1) l'émergence de signaux sensoriels provenant des viscères, (2) l'action de régulation en charge de l'homéostasie, (3) la modification de l'état interne par l'action.

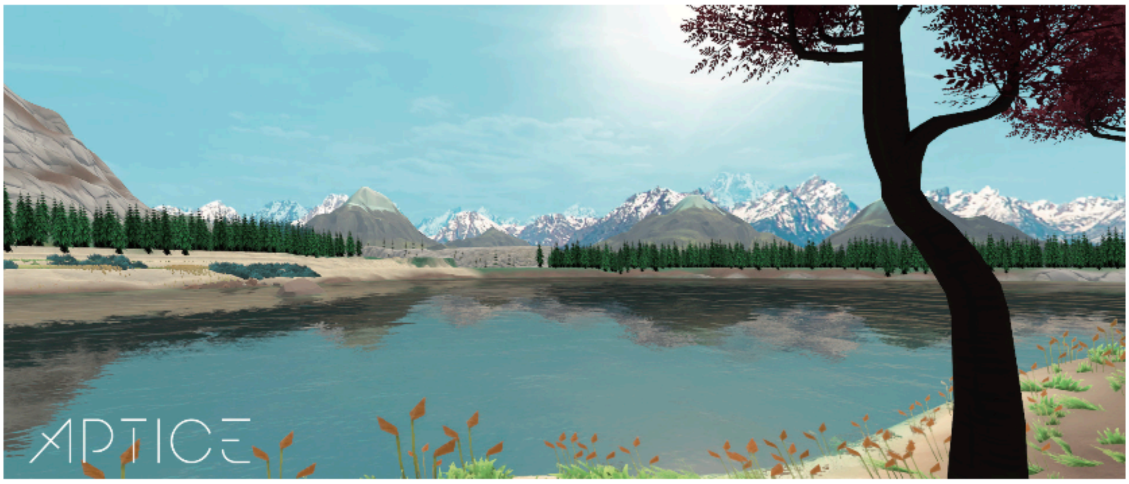
L'activité physique est largement étudiée au sein de la littérature pour ses bénéfices sur la santé et particulièrement par les équipes scientifiques s'intéressant à l'impact de la microgravité pour en contrer les effets néfastes. Cependant, ces bénéfices sont majoritairement étudiés dans le cadre de la décompensation qui survient par le changement de gravité. Ils ne sont pas étudiés en termes d'amélioration de l'adaptation non plus physique (e.g., atrophie musculaire) mais psychique (e.g., humeur, sommeil, perception du stress, émotions). Une étude précédente menée à bord d'un sous-marin nucléaire lanceur d'engins (*sub-surface ballistic nuclear-powered missile submarines*, SSBN) a montré que même si l'activité physique pouvait être une contre-mesure efficiente, elle n'était pas suffisante pour maintenir une gestion émotionnelle stable au cours de la mission (Martin-Krumm et al., 2021). Par conséquent, cette étude suggère que l'activité physique immersive pourrait constituer un apport bénéfique pour augmenter les informations sensorielles lors de la pratique de l'activité physique pour augmenter les bénéfices en termes de santé mentale et physique. En effet, la réalité vituelle (*virtual reality*, VR) est une technologie immersive intégrant des signaux multimodaux permettant de renforcer l'intégration sensorielle et ainsi maintenir les perceptions de contrôle des individus sur leur environnement.

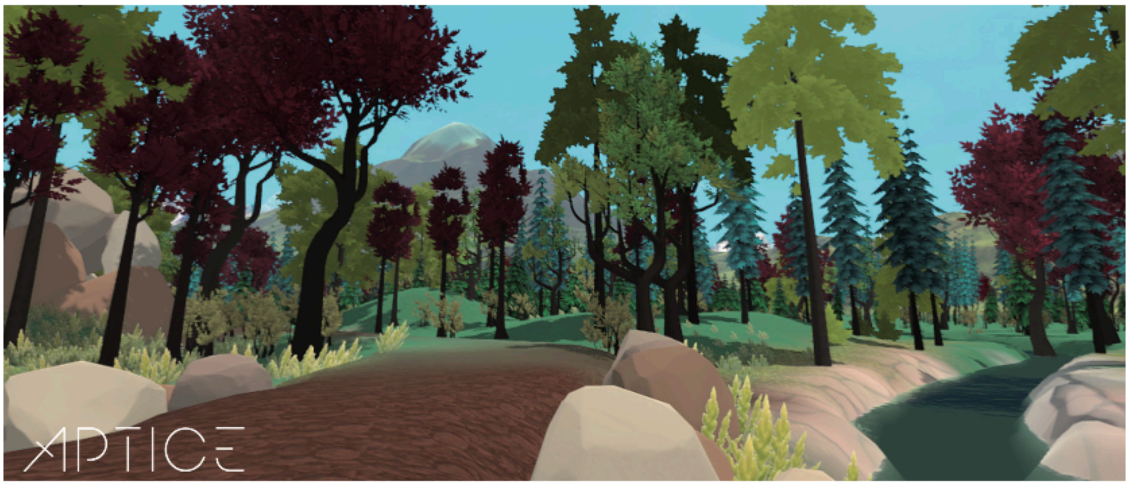
Peu d'études ont été menées sur les bénéfices de l'activité physique immersive comme contre-mesure au maintien de l'état de santé, que ce soit en ICE/EUE ou de manière hypothétique dans le contexte spatial. En conséquence, un nouveau dispositif immersif nommé APTICE, constitué d'un ergocycle couplé à un casque de VR a été développé avec le soutien de la Direction Générale de l'Armement (projet n°2016/017/S). Il était important d'étudier l'acceptabilité et les bénéfices du système APTICE en laboratoire pour évaluer les processus d'adaptation qu'il met en jeu.

L'étude APTICE a porté sur un exercice physique en VR de 20 minutes. Elle avait pour objectif principal d'étudier l'association de la VR avec l'activité physique situé dans un environnement immersif en pleine nature pour améliorer l'état psychologique et les processus sous-jacents. Cet objectif visait à ouvrir la voie vers une application en environnement analogue spatial mais en médecine.

Nous posons l'hypothèse que des changements positifs dans l'état psychologique seraient associés au flux et à la présence pendant la session d'activité physique dans l'environnement VR. Également, la MD et la disposition d'immersion devraient être positivement liées au changement de l'état psychologique, du fonctionnement optimum (i.e. flow) et de la présence. Nous avons également fait l'hypothèse qu'il existe une relation entre l'évaluation subjective des informations sensorielles, la disposition à s'immerger, la MD, et le vécu psychologique de l'expérience APTICE.


APTICE


APTICE


APTICE

Virtual Exercise in Medicine :

A Proof of Concept on Healthy Population

En cours de publication[15]

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Abstract

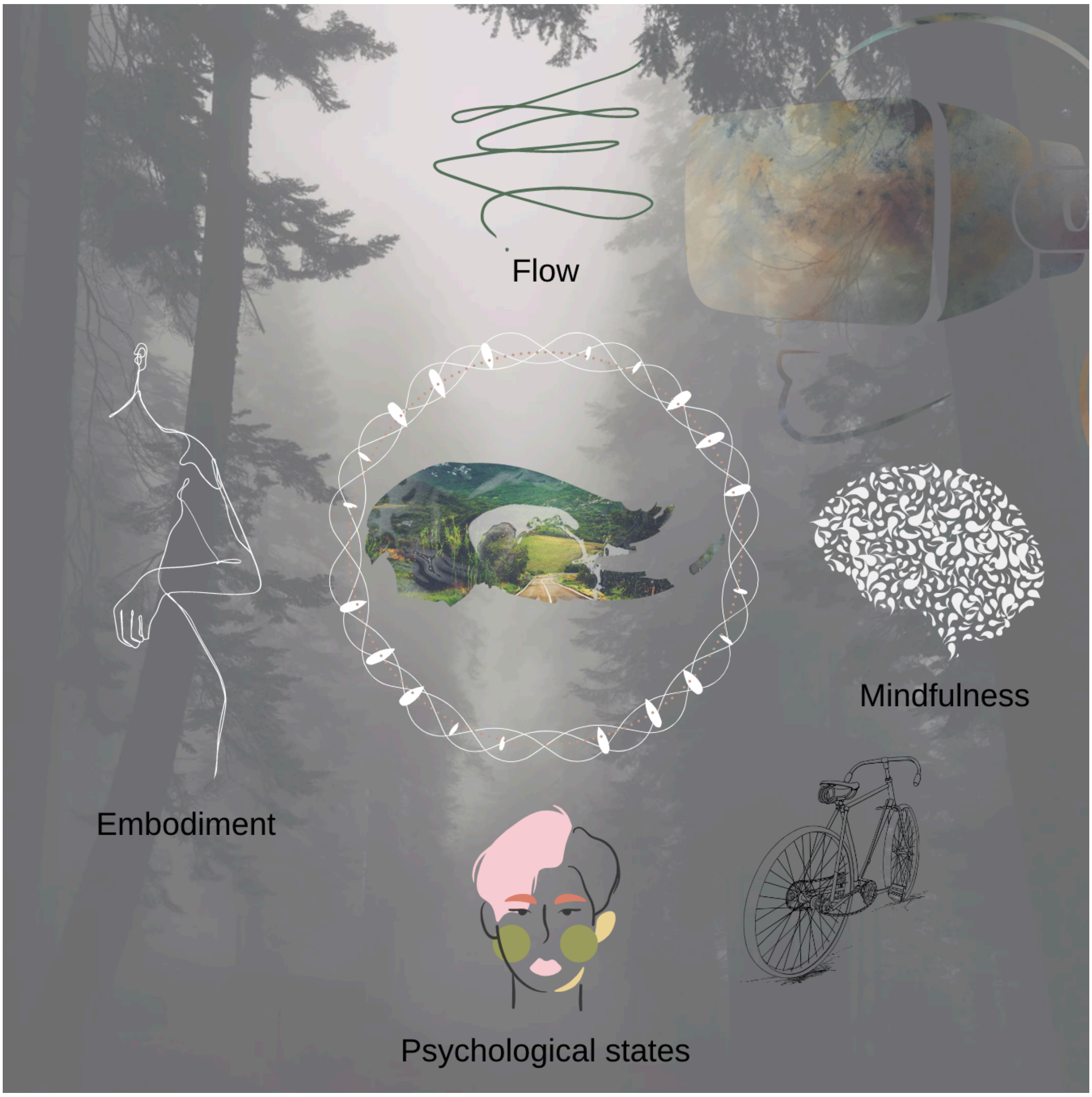
Introduction: Science is beginning to establish the benefits of the use of virtual reality (VR) in healthcare. This therapeutic approach may be an appropriate complementary treatment for some mental illnesses. It could prevent high levels of morbidity, and improve the physical health of patients. For many years, the literature has shown the benefits of physical exercise for health. Physical exercise in a VR environment may improve the management of mild-to-moderate mental health conditions. In this context, we developed a virtual environment combined with an ergocycle (the APTICE system). The aim of this study is to investigate the impact of physical exercise in a VR environment.

Methods: A population of 14 healthy subjects (11 men and three women, mean age 43.28), undertook 15 minutes of immersive physical exercise using the system. Measures included mindfulness and immersion disposition, subjective perceptions of sensory information, user experience, and VR experience (i.e., psychological state, flow, presence).

Results. First, our results highlight that the APTICE system appears to be a useful tool, as the user experience is positive (AttrackDiff's subscales: pragmatic quality = .99; hedonic quality-stimulation = 1.90; hedonic quality-identification = .67; attractiveness = 1.58). Second, the system can induce a positive psychological state (negative emotion, P = .06), and an experience of flow and presence (P-values ranging from <.001 to .04). Third, individual immersive and mindful disposition play a role in the VR experience (P-values ranging from <.02 to .04). Finally, our findings suggest that there is a link between the subjective perception of sensory information and the VR experience (P-values ranging from <.02 to .04).

Conclusion. These results indicate that the device is well accepted with positive psychological and exteroceptive outcomes. Overall, the APTICE system could be a proof-of-concept to explore the benefits of virtual physical exercise in clinical medicine.

Figure 26
Graphical abstract APTICE



Keywords

Countermeasures, Mental health, Physical activity, Virtual reality, User experience

1. Introduction

The Roman poet Juneval wrote, mens sana in corpore sano (a healthy mind in a healthy body). Still relevant today, it has never made as much sense. The body and the mind seem to be indivisible, truly part of a whole [1].

1.1. Virtual reality

In recent years, virtual reality (VR) has been recognized as a new approach to health [2–5] that seeks to connect body and mind [6]. The term was first used by Jaron Lamier in 1986, to refer to an advanced technological interface in which the user interacts with a 3-dimensional environment that is generated by a computer to simulate real-world experiences [7, 8]. The tool can simulate reality and stimulate the body's senses in ways that are only limited by our imagination. It creates a new space-time that is halfway between the real and the unreal, pushing back the boundaries of reality and experimenting with new paradigms that we would not otherwise have access to [9, 10]. Thus, VR goes beyond a simple simulation of the external world. The modulation of interoceptive, exteroceptive, and vestibular information leads the participant to create a representation of their own body. This conceptualization is described as the *body matrix*, which refers to the multisensory representation of the body in the brain, and the space directly around the body [11]. Through VR, it is possible to induce the illusion of being and moving in a fake body. This interstice allows individuals to perceive, interpret, and interact with their environment through an internal representation of the world [12]. Repeated VR use may stimulate changes in the brain, based on neuroplasticity mechanisms [13]. Riva et al. [6] note that effects may be heightened by immersive VR systems, and the induced sense of presence in the surrounding virtual environment.

Immersion is a characteristic of VR systems and is created when the virtual environment replaces the user's sensory stimuli with virtual sensory stimuli. Through immersion it is possible to induce the sense of *presence*. Multisensory integration generates a feeling of *being there* and can sometimes lead to the illusion of being in an alternative body [14, 15]. Slater [16] defined presence as « the strong illusion of being in a place despite the sure knowledge that you are not there » (p. 3551). Thus, subjects have the strong illusion of being in the virtual environment and being able to perceive what is happening in it such as the virtual precipice. However, they consciously know that this is only a perceptual illusion, not a reality [17]. Presence is related to *flow*, which refers to « the holistic sensation that people feel when they act with total involvement » (p. 36) [18]. It is a psychological state corresponding to enjoyment, cognitive absorption, and time/ perception distortion. The literature on VR highlights the influence of immersion, induced by VR systems, on both presence and flow in the virtual environment [19, 20].

Nevertheless, interindividual differences have been noted regarding both presence and flow. One relevant factor seems to be mindfulness disposition (MD). MD is characterized by the awareness that emerges when paying purposeful attention to the present moment, and responding non-judgmentally to the unfolding experience [21, 22]. It is associated with a protective function in both a healthy population and patients [23, 24]. A recent study by Lefranc et al. [25] highlighted that high MD is associated with better positive emotions, interoception, and subjective extra-sensory acuity. Top-down conceptual representations, and bottom-up multisensory inputs contribute to body awareness. Moseley et al. [11] suggested that these representations are integrated with exteroceptive data in the body matrix.

Over the years, VR has become increasingly accessible. It has been particularly beneficial in the field of medicine, whether in the context of medical training, surgery, the treatment of certain neurodegenerative diseases, rehabilitation, pain management, or cognitive and psychological disorders [26–34]. The literature shows the value of using VR as a therapeutic tool to treat mental disorders such as anxiety, depression, post-traumatic stress disorder (PTSD), and phobias [7, 31, 33, 34, 35–38]. Antidepressants, such as selective serotonin-norepinephrine reuptake inhibitors, or benzodiazepines are the first-line treatment for anxiety symptoms in patients, while cognitive-behavioral therapy has been found to be effective in reducing them [39–41]. VR interventions such as exposure therapy have been shown to be effective as a coadjutant in mental illness, and appear to have the same effects as drug treatments, although the results take longer to become apparent [34]. Used as a complementary therapy, VR may have many advantages, including the ability to recreate a realistic traumatic environment under controlled conditions, which can be complex *in vivo* [33, 42, 43]. Most studies show that participants have a high degree of acceptance, and its use is consistent with post-intervention improvements in symptom awareness, a decrease in depressive symptoms, greater motivation to exercise, and better enjoyment, engagement, and affect, particularly in clinical populations [35, 37]. VR therapy can stimulate emotion (notably fear), as the participant has the feeling of being present in the (unreal) environment [44, 17]. Thus, it appears to be an innovative non-drug supplement to other treatments that can be demanding for the patient and may have side effects. Although the quality of the technology may play a role in positive outcomes [45], it appears to be an interesting new tool that poses no serious threat to participants [46].

1.2. The potential of immersive physical activity

In recent years, an increasing body of literature has investigated the power of immersive physical activity. Physical activity preserves health and protects individuals from many pathologies [47–49]. It can be defined as « any bodily movement produced by skeletal muscles that results in the expenditure of more energy than the resting metabolism » (p. 6) [50]. One of the components of physical activity is physical exercise, understood as « planned, structured, repetitive physical activity whose objective is to improve or maintain one or more components of physical fitness » (p. 6) [50]. For many years, the literature has shown the benefits of physical activity on health, not only physical (i.e., reduced mortality, reduced risk of cardiovascular pathologies, reduced incidence of cancer, weight maintenance), but also cognitive (i.e., improved cognitive function, improved sleep, reduced risk of dementia), and psychological (i.e., reduced signs of anxiety and depression, reduced risk of depression), both in the general population (i.e., adults, children, and the elderly), and in the context of various chronic diseases and health conditions [47–49, 51]. However, it is only recently that the scientific community has begun to take an interest in the biological and physiological mechanisms underlying these outcomes [52, 53]. People with mental illness often exhibit disrupted sensory processing and perception [54]. Thus, physical activity therapy can be both a physical and psychological countermeasure. However, compliance is a key issue, as regular practice is necessary for optimal mental illness management.

Few studies have examined the use of VR in this context, although the pioneering work carried out by Plante et al. [55–57] seems to indicate real benefits in terms of well-being, particularly in women [56]. The addition of VR has been found to enhance mood, increase enjoyment and energy, reduce tiredness, enhance motivation and confidence, not to mention increase compliance [57, 58]. Enjoyment may play an important role in the benefits gained from exercise [58].

In recent years, there has been an increase in the number of studies that encourage the practice of sport to prevent anxiety disorders, and protect against anxiety and depression [59, 60]. A recent study demonstrated its importance in the context of the COVID-19 pandemic, where it was able to improve well-being through improved physical and cognitive outcomes, and limit psychological disorders related to isolation and confinement [61]. Thus, the literature suggests that VR coupled with physical activity may be a useful way to improve the symptomatology of individuals with anxiety disorders, PTSD, and depression [61]. Furthermore, many studies have highlighted the ability of natural environments to induce positive emotions, promote well-being, reduce anxiety, improve self-esteem, and reduce negative emotions (i.e., fatigue, confusion, tension, depression, anger-hostility) compared to urban or indoor environments [62, 63]. The same observation has been made in VR environments [64]. A virtual environment that offers physical activity in a natural setting seems to have the potential to improve the benefits of VR, especially for people suffering from mental illness [65, 66].

1.3. Gaps in the literature, and objectives of the study

Many of the systematic reviews and meta-analyses that have been carried out have important limitations, notably related to differences in technology. There is also a lack of longitudinal studies of the long-term effects of VR. Most studies are one-shot experiments that evaluate its benefits before and after the intervention. Evaluation itself is problematical, as subjective measures (questionnaires) are typically used, and few studies measure physiological effects (i.e., heart rate variability, heart rate, electrodermal activity). As it can be complex to overcome these gaps, caution is advised in interpreting any results or conclusions [33, 35, 62, 65, 67, 68]. Given these gaps in the literature, there is a need for more rigorous testing. Any evaluation should be based on three assessment criteria: (i) the activity does not duplicate other countermeasures; (ii) it must improve the experience of sport, and thus increase its attractiveness (especially relevant for patients suffering from depression) [55, 56]; and (iii) immersion must provide a multimodal sensory input to the user [69–72]. The benefits of multisensory stimulation have been demonstrated in the context of cognitive and sensorimotor rehabilitation [73] and emotion regulation [9, 74].

Thus, the aim of this preliminary proof-of-concept study is to investigate the association of VR with physical exercise in a virtual natural environment in improving the psychological state of healthy subjects and the underlying processes, prior to evaluating its benefits in clinical medicine. We measure the user experience (UX) and evaluate three hypotheses: H1: Positive changes in psychological state are associated with flow and presence during the session in the VR environment; H2: Both mindfulness disposition and immersion disposition are positively related to change in the participant's psychological state, flow, and presence; and H3: There is a relation between the subjective evaluation of sensory information, immersive disposition and mindful disposition, and psychological change.

2. Material & methods

2.1. Ethic approval and consent to participate

This research was approved by the Minarm Ethical Committee (N 125 132/MIP/DGA/MINARM). Written consent was obtained from all participants, in accordance with the Declaration of Helsinki and subsequent amendments.

The datasets generated and analyzed during the current study are not publicly available because they are the property of the French Armed Forces Health Service. Although data are not available to the general public, they are available from marion.trousselard@gmail.com on reasonable request.

2.2. Participants

Fourteen volunteers participated (three women, 11 men), declared medically fit, were recruited during the three innovation open days ar the French Armed Forces Biomedical Research Institute (IRBA) in 2019. They ranged in age from 22 to 59 (43.28 ± 10.60) and were either working for IRBA (n = 9) or the French Football Federation (n = 5). See Table 1 for demographic information. They were recruited by e-mail and contacted to determine if they met inclusion/ exclusion criteria. If eligible, they were given an appointment for the laboratory session. All were asked to abstain from exercise on the day of their participation to ensure that results were due to the experiment. Inclusion criteria were based on the following: affiliation to a healthcare system (social security), aged between 18 and 75 years, and no history of neurological or cardiovascular disease, diabetes or medications that could affect the response. Exclusion criteria included pregnancy, the presence of a contraindication to VR (people who had experienced anxiety or nausea during a VR experience, photosensitive epilepsy, vestibular disorder, severe myopia > 3.5 diopters).

This research was approved by the Minarm Ethical Committee (N 125 132/MIP/DGA/MINARM). Written consent was obtained from all participants, in accordance with the Declaration of Helsinki and subsequent amendments.

Table 1

Socio-demographic characteristics of participants

Sociodemographic variables	Data*
N	32
Age	43.28 ± 10.60
Gender (men/women)	11/3
Screen time (professional)	300.00 ± 164.73
Screen time (personal)	111.42 ± 63.95
Physical activity (yes/no)	10/4
Video games (yes/no)	4/8
Ocular correction (yes/no)	10/4

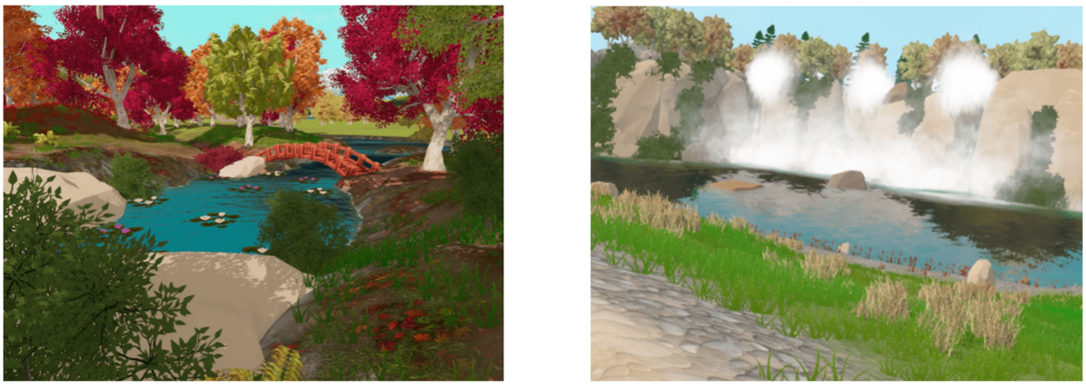
*Mean and standard deviation are reported when necessary. Other figures show the ratio of the number of subjects.

Participants who practiced a physical activity or engaged in video games completed the Addictive Intensity Evaluation Questionnaire (AIEQ). The analysis found that 10 out of 14 participants (85%) engaged in physical activity (31.00 ± 6.20) and four out of the 14 (35%) played video games (28.20 ± 14.34). No addictive behaviors were found among participants in either of these modalities.

2.3. Augmented physical training for isolated and confined environments (APTICE)

This proof-of-concept study is based on the APTICE system. The aim of the system is to use physical exercise in a VR environment to improve well-being in depressive patients. It is composed of a VR-enabled cycle ergometer (VirZOOM Bike Controller; Cambridge, MA), and a VR Head Mounted Display (Oculus Rift CV1, Oculus VR; Menlo Park, CA), which provides visual and auditory inputs. The VR application was developed by GAMIT (Petit-Quevilly, France) and ran on an Asus A15 TUF566IU-HN326T with an AMD Ryzen 5 4600H 16 GB processor, a 512 GB SSD, and a Nvidia GeForce GTX1660 Ti 6 GB graphics card. The VR environment consisted of natural areas of forests and mountain plains (Figure 1).

Figure 1
Natural virtual environment images. (a) Forest with stretches of water; (b) Mountain plain with sheep.



(a) (b)

2.4. Data collection

A 7-item socio-biographic questionnaire (SbQ) was developed to collect standard socio-demographic data such as gender, age, hobbies, physical activity, video game use, and VR experience. The AIEQ evaluated addictive practices [75]. Two versions were used: the 14-item AIEQ-g that measures the intensity of video game playing, and the risk of its problematic use; and the 14-item AIEQ-s that measures sport practice, and the risk of its problematic use.

2.5. UX of the APTICE device

The APTICE UX was assessed using the 10-item AttrakDiff questionnaire, which evaluates the hedonic and pragmatic qualities of interactive systems [76]. It is divided into four subscales: pragmatic quality, hedonic quality-identity, hedonic quality-stimulation, and attractiveness. Values close to the mean (from 0 to 1) are considered standard. They indicate that the device meets its objectives with no negative impacts on the user.

2.6. Psychological questionnaires

Two questionnaires evaluated psychological disposition. The 14-item Freiburg mindfulness inventory (FMI) was used to measure mindfulness disposition [77]. It is divided into two subscales: acceptation and presence. Immersion disposition was assessed using the 18-item immersive tendencies questionnaire (ITQ-f), which is divided into four subscales: focus, involvement, emotions, and games [78]. Two questionnaires evaluated psychological state. First, the 12-item Scale of Positive And Negative Experience questionnaire (SPANE) assessed subjective feelings of well-being [79]. The overall scale is divided into two subscales: positive and negative emotions. Second, the 20-item Activation-Deactivation Adjective CheckList (AD-ACL) evaluated the level of awareness and emotional disposition [80]. This is divided into two dimensions: energic arousal (EA, from energy to tiredness) and tense arousal (TA, from tension to calmness). The EA is further divided into two subscales: general activation and deactivation, while the TA is subdivided into general tenseness and calmness.

2.7. Subjective evaluation of the quality of sensory information

We developed the Personal Evaluation of Six Senses (PESS) questionnaire to assess subjective perceptions of: vision, sound, touch, olfaction, taste, and equilibrium. Participants evaluated the accuracy of their perceptions from each of their six senses using a ranked scale running from 1 to 6.

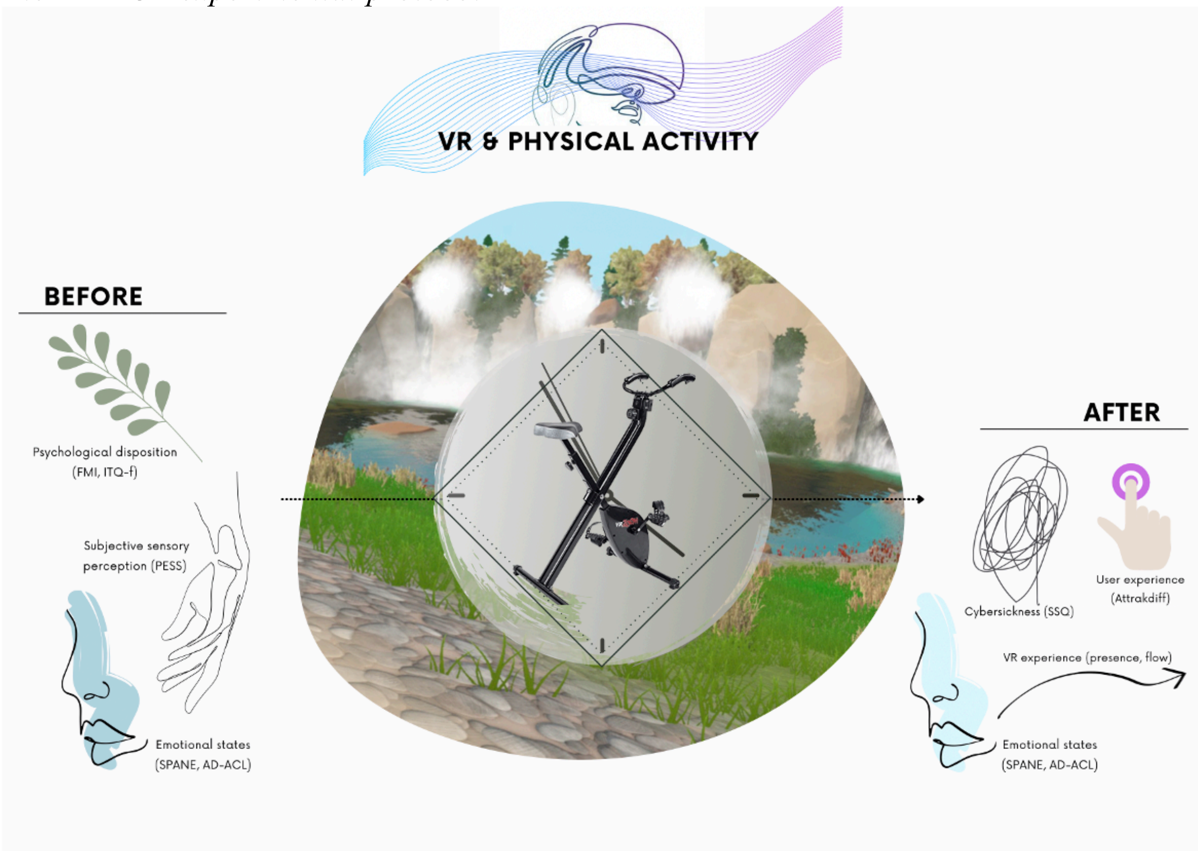
2.8. The VR experience

The VR experience was assessed using the 12-item Educational Flow Questionnaire (EduFlow2), which measures flow [81]. It is divided into four dimensions: cognitive control; immersion and time transformation; loss of self-consciousness; and autotelic experience. Cognitive absorption (a summary of the first three dimensions] was added as a fourth scale. The 24-item Presence Questionnaire (PQ-f) assessed presence [82]. It is divided into seven subscales: realism, possibility of action, quality of interface, possibility of examination, self-evaluation of performance, sounds and haptic. APTICE sickness was assessed using the 16-item Simulator Sickness Questionnaire (SSQ) [83]. It is divided into two subscales: nausea and oculo-motor.

2.9. Procedure

The experimental protocol is shown in Figure 2. Upon arrival, participants were asked a few questions to ensure they met inclusion criteria and signed the consent form. They then completed a series of questionnaires in the following order: SbQ, AIEQ-g, AIEQ-s, FMI, PESS, ITQ-f, SPANE, and AD-ACL. Then, they engaged in a moderate intensity bout of exercise in a natural environment for 15 minutes, while wearing the VR headset. They could choose their trajectory along various predefined paths and, by turning their head, could get a 360-degree view of the virtual environment. At the end of the session, they were asked to complete another series of questionnaires in the following order: SPANE, AD-ACL, EduFlow2, PQ-f, AttrakDiff, and the SSQ).

Figure 2
The APTICE experimental protocol



2.10. Statistical analysis

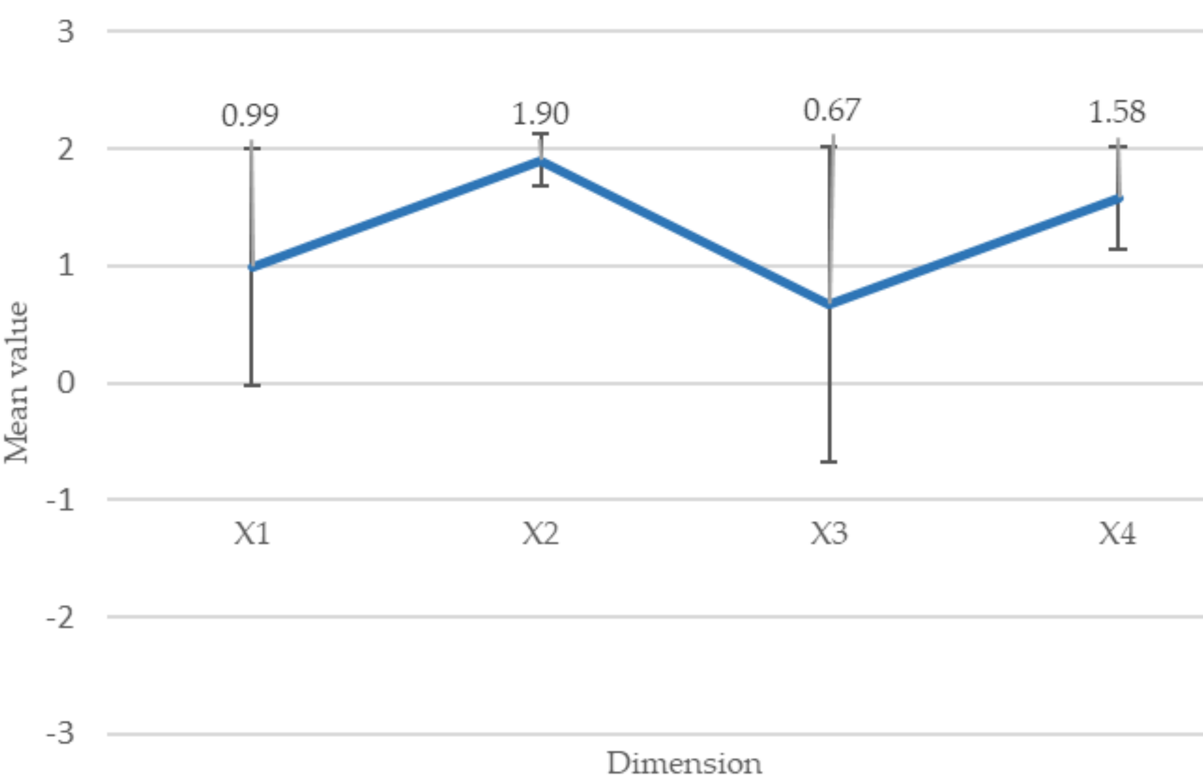
Statistical analyses were run using RStudio (Boston, v. 1.2 5001). Descriptive statistics were expressed as mean ± SD. The Shapiro Wilk test was used to determine whether data were normally distributed. The effects of the APTICE experience on emotional and activation-deactivation states were assessed as follows: a *t*-test for pre-post comparisons and parametric data, or the Mann-Whitney test for non-parametric data. Kendall's correlations were run to explore the relationship between virtual exercise, subjective sensory accuracy, and VR experience. For all analyses, significance was set at $P < 0.05$. Trends were considered when $0.05 < P < 0.10$. Deltas were calculated to compare the temporal impact of the experience measured using the SPANE and the AD-ACL.

3. Results

3.1. The UX

The APTICE tool was assessed in terms of the UX. Participants reported a positive experience measured as pragmatic quality, hedonic quality (stimulation), hedonic quality (identification) and attractiveness (Figure 3). Scores were particularly high for hedonic quality (stimulation) and attractiveness. No participants reported any cybersickness.

Figure 3
AttrakDiff's subscales. Values close to the mean (from 0 to 1) are considered standard, and indicate that the device meets its objectives with no negative impacts on the user. However, they also suggest that improvements could be made to the system in order to obtain high positive values. Values outside this neutral zone are considered positive (1 to 3) or negative (-1 to -3). X1: Pragmatic quality; X2: Hedonic quality (stimulation); X3: Hedonic quality (identification); X4: Attractiveness.



3.2. Relationships between psychological assessments, exteroception and VR experience

Table 2 summarizes the significant correlations between tested variables.

Table 2

Significant correlations between tested variables as a function of the three hypotheses

H1: the VR experience (change in psychological state, flow, presence)	$\tau^{a,b}$	*p*-value[c]
Delta AD-ACL tense activation – Flow-Autotelic experience	−0.52	.01
Delta AD-ACL tense activation – Flow Immersion and time transformation	−0.46	.04
PQ-f Haptic – Flow Loss of self-consciousness	−0.52	.02
PQ-f Realism – Flow Cognitive control	0.52	.01
PQ-f Possibility to examine – Flow Cognitive control	0.45	.000
PQ-f Possibility to examine – Flow Cognitive absorption	0.67	.001
PQ-f Possibility to examine – Flow Immersion and time transformation	0.55	.01
PQ-f Possibility to act – Flow Cognitive absorption	0.58	.004
PQ-f Possibility to act – Flow Cognitive control	0.76	.000
PQ-f Possibility to act – Flow Immersion and time transformation	0.58	.006
PQ-f Possibility to act – Flow Autotelic experience	0.58	.001
H2: Disposition and the VR experience (change in psychological state, flow, presence)		
Delta AD-ACL general activation – ITQ-f Involvement	−0.52	.02
Delta AD-ACL tense activation – ITQ-f Games	0.45	.04
FMI Acceptation – PQ-f Possibility to examine	0.49	.02
FMI Acceptation – Flow Cognitive control	0.45	.03
ITQ-f Involvement – Flow Loss of self-consciousness	0.54	.01
H3: Subjective exteroceptive accuracy, disposition, and the VR experience (change in psychological state, flow, presence)		
Vision – ITQ-f Involvement	0.48	.03
Smell – ITQ-f Focus	−0.43	.04
Hearing – Flow Cognitive absorption	−0.43	.04

Hearing – Flow Immersion and time transformation	−0.47	.03
Taste – Flow Cognitive control	−0.49	.02

*p-value for analysis of unit group effect.

3.2.1. H1: The VR experience (change in psychological state, flow, and presence)

The analysis of emotional and arousal states only identified a trend for negative emotions. Participants tended to have less negative emotion after the APTICE experiment ($t = 2.06$, $df = 12$, $P = .06$).

There were significant positive and negative correlations between flow and presence. Subjects who scored high for *possibility to examine* also scored high for *flow cognitive control* ($\tau = 0.45$, $P < .001$), *flow cognitive absorption* ($\tau = 0.67$, $P = .001$), and *flow immersion and time transformation* ($\tau = 0.55$, $P = .01$). Subjects who scored high for *possibility to act* also scored high for *flow cognitive absorption* ($\tau = 0.58$, $P = .004$), *flow cognitive control* ($\tau = 0.76$, $P < .001$), *flow immersion and time transformation* ($\tau = 0.58$, $P = .006$), and *flow autotelic experience* ($\tau = 0.58$, $P = .001$). As *realism* increased, *flow cognitive control* increased ($\tau = 0.52$, $P = .01$). However, as *haptic* increased, *flow loss of self-consciousness* ($\tau = -0.52$, $P = .02$) decreased.

Concerning change in psychological states related to flow and presence, our results suggest that there is no correlation between change in emotional state (measured with the SPANE) and either flow or presence. However, there were significant negative correlations between flow and change in activation-deactivation states (AD-ACL). An increase in *tense activation* (positive delta) was associated with lower scores for *flow immersion and time transformation* ($\tau = -0.46$, $P = .04$), and *flow autotelic experience* ($\tau = -0.52$, $P = .01$). No correlation was found between presence and flow, and change in activation-deactivation.

3.2.2. H2: Disposition and the VR experience (change in psychological state, flow, and presence)

No relationship was observed between immersive disposition and MD for any subscale.

The analysis found a significant positive correlation between MD and presence. More precisely, higher *MD-acceptation* was associated with a higher score for *possibility to examine* ($\tau = 0.49$, $P = .02$). There was also a significant positive correlation between MD and flow. High scores for *MD-acceptation* were associated with high scores for *flow* *cognitive control* ($\tau = 0.45$, $P = .03$). Finally, there was a significant positive correlation between immersion and flow. Specifically, high scores for *flow loss of self-consciousness* were slightly associated with high scores for *involvement* ($\tau = 0.54$, $P = .01$).

Concerning disposition and the VR experience, the analysis found no correlation between change in emotional state and either immersive or mindful disposition. Second, significant positive and negative correlations were found between immersion and change in activation-deactivation. An increase in *tense activation* (positive delta) was associated with higher scores for *games* ($\tau = 0.45$, $P = .04$). However, an increase in *general activation* (positive delta) was associated with lower scores for *involvement* ($\tau = -0.52$, $P = .02$).

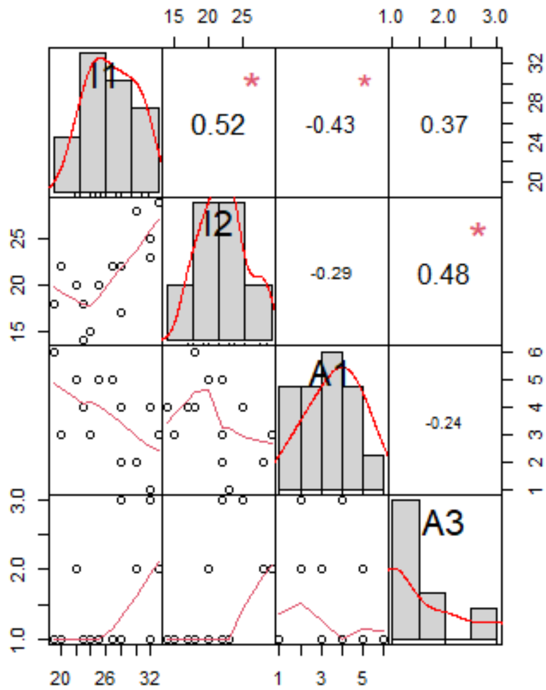
3.2.3. H3: Subjective exteroceptive accuracy, disposition and the VR experience

The analysis found no relation between the subjective exteroceptive evaluation and change in emotional and activation states, presence, or MD. However, significant positive and negative correlations were found between immersion and subjective acuity.

Correlation matrices for immersion and subjective acuity variables are shown in Figure 4. Distributions are shown on the diagonal. Trend curves are shown at the bottom of the diagonal scatter plots. The top diagonal shows correlation coefficients and significance levels (asterisks). *P*-values (0, 0.001, 0.01, 0.05, 0.1, and 1) are shown as ('***', '**', '*', ',', '.' and '').

Increased *involvement* was associated with higher subjective *visual acuity* ($\tau = 0.48$, $P = .03$). On the other hand, an increase in *focus* was associated with lower subjective *smell* acuity ($\tau = -0.43$, $P = .04$). Low scores for subjective *hearing* were associated with high scores for *flow cognitive absorption* ($\tau = -0.43$, $P = .04$), and *flow immersion and time transformation* ($\tau = -047$, $P = .03$). Similarly, low scores for subjective *taste* were associated with high scores for *flow cognitive control* ($\tau = -0.49$, $P = .02$).

Figure 4
*Correlation matrices for immersion and subjective acuity variables. Distributions are shown on the diagonal. Trend curves are shown at the bottom of the diagonal scatter plots. The top diagonal shows correlation coefficients and significance levels (asterisks). P-values (0, 0.001, 0.01, 0.05, 0.1, and 1) are shown as ('***', '**', '*', ',', '.'). I1: Focus; I2: Involvement; A1: Olfaction; A3: Vision.*



4. Discussion

4.1. Main findings

The main aim of this proof-of-concept study was to investigate the effect of VR associated with physical activity on the psychological state of healthy subjects, prior to further evaluation with depressive patients in a randomized controlled trial. This exploratory study evaluated a new device, named APTICE, which couples physical exercise with a VR headset. This pilot feasibility study proposed variables of interest, which will form the basis for our next randomized controlled trial. The latter will investigate clinical and neuro-functional subtracts in a population suffering from depression using VR associated with physical activity. Our present results provide new insights on the benefits of this type of technology when used in clinical medicine to improve health.

4.2. A positive UX experience

As Hassenzahl et al. [84] demonstrate, the evaluation of the hedonic and pragmatic qualities of a system is known to influence overall perceptions of its attractiveness. Understanding the UX is a crucial point in the design of a new device, which is often ignored. Participants in our study were very positive regarding both the *hedonic quality stimulation* and the *attractiveness* of the device. However, *pragmatic quality* and *hedonic quality identification* scores were lower. Furthermore, responses were most disparate for these two dimensions. *Hedonic quality stimulation* was associated with ideas such as ‘outstanding’, ‘impressive’, ‘exciting’, or ‘interesting’. Although the response to the UX appears to be positive, there is still room for improvement. The relatively low scores for *hedonic quality identification* are not surprising, as this aspect relates to the ability of the system to reflect the user’s identity. Similarly, *pragmatic quality* needs to be improved, with a focus on usability. Both the appropriateness of the functionality and its accessibility need further attention. However, this short, 15-minute experiment allowed us to conclude that APTICE meets its development and quality objectives; specifically, to design a device that supports physical exercise in VR. In the longer term, we will need to consider how to improve it, particularly in light of the technological development that has taken place since its creation.

4.3. Psychological changes induced by the APTICE device

Our main hypothesis was that physical exercise in a VR environment could create a positive experience, measured as psychological and sensory feedback from participants.

Consistent with the literature, our initial results suggest that the APTICE experience decreased negative emotions [44, 85–89]. However, our first hypothesis (that APTICE would induce a positive psychological state and an experience of flow and presence) was only partially confirmed. The literature [6, 16] notes that presence and flow are usually positively linked, although a negative correlation has been found between haptic presence and loss of self-consciousness in flow experiments. In the absence of a meaningful haptic system, interactions with objects in the VR environment can widen the gap between actual and virtual realities [90]. In our experiment, haptic feedback from the interaction with the ergocycle did not reflect reality which suggest its key role in inducing flow. For example, there was no body movement when going around bends, and almost no return on effort. The poor quality of the correspondence between the virtual exercise environment and reality could explain the absence of a change in positive emotions.

Our initial results propose a close relation between the quality of the technology and the VR experience. This is all the more important as flow (characterized by a deep involvement and absorption in an activity) promotes a state of inner well-being and positive emotions [91, 92]. Overall, our results suggest that practicing a physical activity in a VR setting could be used to improve psychological outcomes. Following previous studies [60, 61, 66], the APTICE device may induce potential benefits for patients, especially those suffering from mental illness. The literature also shows that natural scenes support a positive psychological state both in general [65, 86], and in the treatment of mental illness [67, 93]. This is in line with the reduction of negative emotions in individuals following our study APTICE session. Although APTICE needs improvement, both the positive response to the UX and its effect on the user's psychological state suggest that regular use may have a positive impact on mental health.

4.4. Relationships between disposition and VR experience

Our results partially confirm our second hypothesis, which focused on the impact of immersive disposition and MD on the VR experience. First, we found no relationship between immersive disposition and MD in our sample. Immersive disposition is used to evaluate the potential to immerse a subject in a situation, while MD is characterized by the ability to be in the here-and-now. It is therefore possible that these two dimensions are unrelated. Our experiment showed that the involvement subscale of immersive disposition was associated with a loss of self-consciousness in terms of flow effect. An individual's interest in a target object [94], or their motivational state in relation to a target object [95] have been described as conditions for flow experience in VR [96]. Furthermore, our experiment found that immersion was unrelated to presence, which conflicts with the literature [14, 37]. A key difference compared to earlier work is that our subjects were asked to make a physical effort. It is possible that this effort counteracted their immersive disposition. If we turn to the relationship between MD, presence and flow, acceptance seems to be the most relevant dimension. Acceptance consists of accepting inner events, such as emotions, thoughts, or beliefs as they are felt

[97]. It does not mean resignation, but rather perceiving one's own experience with an attitude that acknowledges it, rather than judging it as either good or bad. Thus, the ability to accept what is happening now may be a more useful way to examine presence and cognitive control than simply being in the here-and-now. Taken together, these results suggest that physical exercise in the VR may be improved by acceptance that enhances the feeling of presence.

4.5. APTICE device and exteroceptive modulations

Our final hypothesis concerning the relation between subjective exteroceptive perceptions of sensory information and physical exercise in the VR experience is exploratory. On the one hand, our results show that there is an assumption that information provided by all five senses may help the user to become immersed in the experience of where they are, whom they are with, and what they are doing. The feeling of a real experience gives rise to presence. On the other hand, mindful participants pay more attention to information from their body, leading to better adaptation to the environment [98]. Using fMRI, Farb et al. [99] identified several brain regions associated with mindfulness. In particular, they found that deactivation of the medial prefrontal cortex, and increased activation of parietal areas was associated with proprioception and sensory-motor body experiences. Mehling [100] reports the use of external stimulation when trying to understand how felt sensations are used internally to regulate stress or attention. Such information is integrated and linked to the person's emotional state, as a function of whether the body is experienced as safe or not [98, 100].

Our results suggest that subjective preferences in exteroception-perception are linked to the experience of physical exercise in the VR environment. Furthermore, they show that immersion is correlated with subjective visual acuity. Subjects in our experiment cycled in a virtual environment based on natural visual information. Unsurprisingly, high scores for subjective visual acuity were associated with flow. Many studies have highlighted the potential of external sensory information to enrich the lived experience [101–104]. Exteroception information can generate intense emotional processes [154] and flavor the manipulation within the VR [101–104]. However, the evidence is weak, and it is also possible that such an environment may inhibit VR experiences, due to its limited capacity to provide wider sensory inputs [105]. Another outcome of our work is that individual preference may play a role in the VR experience. Our findings show that this experience is negatively associated with all forms of external sensory stimulation (i.e., hearing, taste, smell) except vision. This suggests that other senses are partially inhibited, and only vision is recruited on a large scale. Vision is an essential component of the APTICE experience.

In this context, Slater and Usoh [106] suggest that an individual's experience is encoded by visual, auditory, and kinesthetic systems of representation. Depending on the context, the person will naturally tend to favor one system over another. However, the latter authors note that the visual system predominates in individuals who report a higher sense of presence, and those who process information in the first person. Thus, individual characteristics may be a key factor in any experiment. Overall, our study implies that APTICE may alter multisensory representations during physical exercise. Future work should address this issue, which remains unexplored.

4.6. Future clinical applications

VR technologies appear to complement established approaches to mental healthcare. Its association with physical activity makes it an interesting new approach that merits further attention. Furthermore, the use of VR in healthcare is expanding rapidly. There are many new opportunities in clinical medicine, including mental illness, where VR may be an alternative treatment [3, 4, 107, 108]. Our findings validate the impact of physical exercise in a VR environment on negative emotions in a healthy population. Although our results should be taken with caution, due to the small sample size, they highlight the importance of better-understanding the processes involved in healthy subjects. Beyond the efficacy of interventions to understand which populations might benefit from VR combined with physical activity, it is important to understand the processes that predispose this state in healthy individuals. Further studies with larger samples will be needed to evaluate the role of these processes in clinical research. Thus, the next step is to study clinical and neuro-functional subtracts in a population suffering from depression before, hopefully, proposing the tool as a countermeasure (ID-RCB: 2020-A03415-34) for this population and other people in healthcare. There is an untapped opportunity to use VR as a prevention tool and target the processes that make an individual poorly adapted to the environment. This is particularly the case for people who work in challenging confined and isolated environments, or extreme and unusual environments [65].

5. Limitations

The study has four main limitations. The first, and most important, is the small sample size. This study is intended to be a pilot feasibility study that will support a future controlled randomized trial. In this context, it validated the usefulness of the APTICE system, and highlighted the interaction between variables of interest. In the next phase of our work, we will launch a larger clinical study in participants with depression. The second limitation relates to the use of subjective self-report measures. An objective sensory evaluation needs to be developed for healthy subjects, which would help researchers to better-investigate the human-body relationship. Subjective variables should be combined with physiological measures, such as heart rate variability. Thirdly, our results cannot be generalized due to the fact that the population was recruited from among armed forces personnel and footballers, who are usually different from the general population in terms of fitness and psychological state. The last issue concerns the VR equipment used in our experiment, which is becoming dated. A new version of the Oculus headset is already available, with a better graphics interface.

6. Conclusion

This exploratory proof-of-concept study investigated some of the processes implicated in physical exercise in a VR environment, with the aim of better-understanding their relationship with psychological state in a sample of healthy subjects. It represents the first step in a larger, randomized controlled trial that will investigate clinical and neuro-functional subtracts in a population suffering from depression. Our results suggest that the APTICE environment is able to change negative emotional states consistent with the experience of flow and presence. Moreover, our findings demonstrate that immersive and mindful disposition play an important role in the VR experience. Finally, they also suggest that the subjective exteroceptive perception of sensory information may be a key aspect, and seems to indicate that one sense may prevail over another at the level of the individual. Our study has several implications for clinical medicine: (1) VR can help to enhance and reinforce the beneficial actions of physical activity; (2) APTICE is a promising system and may be effective in improving mental health; and (3) APTICE has the potential to be used as an alternative treatment to drugs and to improve quality of life. However, many questions remain unanswered, and further work is needed to exploit the potential of VR associated with physical activity both as prevention and treatment.

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Synthèse des résultats principaux

L'étude APTICE avait pour objectif d'étudier l'association d'une activité physique sur ergocycle pendant 20 minutes et de la VR immergeant le cycliste dans un environnement en pleine nature comme activité physique permettant d'améliorer l'état psychologique post activité. Cette étude visait aussi à explorer les processus psychologiques de présence et d'immersion pour évaluer leur implication dans les bénéfices psychologiques de l'expérience APTICE. Il s'agissait également d'une étude exploratoire pour un déploiement en médecine dans le cadre de la dépression, pathologie fréquemment rapportée à l'issue de mission en ICE/EUE.

Nos résultats mettent en évidence que l'activité physique immersive à travers la technologie APTICE a tout son potentiel pour constituer une contre-mesure efficiente en améliorant l'état psychologique. Elle permet d'induire une expérience utilisateur positive ce qui traduit une bonne acceptabilité de l'outil par les individus. Elle génère une expérience de flow et de présence nécessaire à tout dispositif immersif, liée aux informations extéroceptives et en lien avec la MD. Trois implications pour la médecine clinique ont pu être soulignées : (1) la VR aide à améliorer et à renforcer les actions bénéfiques de l'activité physique, (2) APTICE est un système prometteur permettant l'amélioration de la santé mentale, et (3) ce système a le potentiel d'être utilisé comme traitement alternatif non pharmacologique et améliorer la qualité de vie.

Ces résultats exploratoires s'inscrivent dans le cadre de l'*embodied medicine.* Cette approche, définie par Riva et al. (2017 ; 2019), indique que la VR pourrait permettre de modifier la perception de soi, de son corps et donc de l'incarnation au sens de la représentation du corps. La modulation des informations intéroceptives, extéroceptives et vestibulaires conduit à une représentation de notre propre corps, un symbole de la perception (Riva, 2018). Ce cadre relativement récent a fait l'objet d'une roadmap (Khalsa et al., 2018) qui amène à proposer de nouvelles approches pour améliorer l'état de santé.

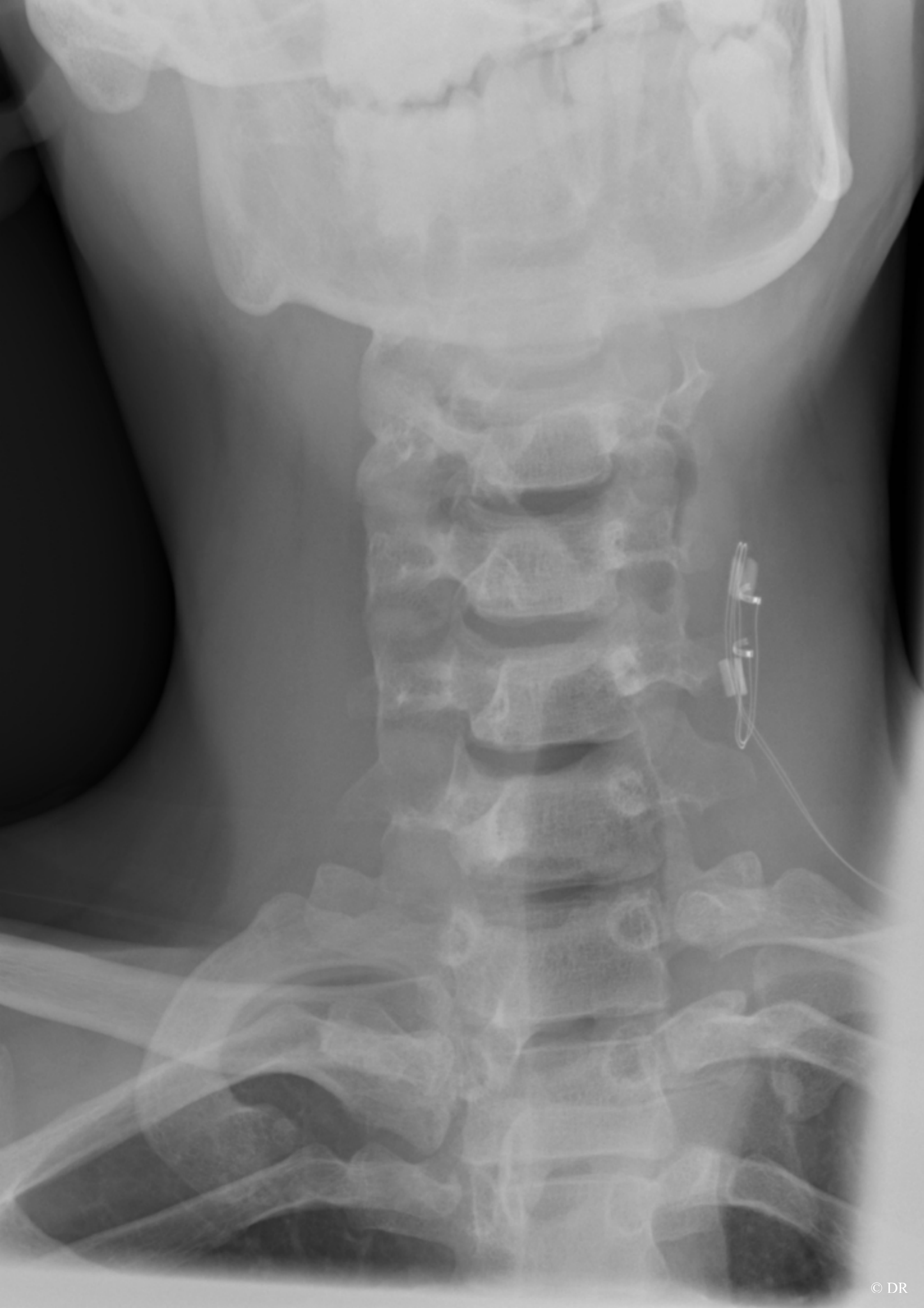
La dernière approche de ce travail cible l'amélioration/le renforcement du tonus parasympathique. Il s'agit par cette cible mécanistique d'améliorer la HRV et ainsi d'apporter des bénéfices pour la santé et l'adaptation. Précédemment, nous avons pu souligner les interactions entre les signaux intéroceptifs et ceux issus de l'ANS (Berntson et al., 2019). Elles contribuent à la communication bidirectionnelle corps-cerveau et ont des répercussions sur la gestion des réponses psychologiques, physiologiques, cognitives et sensorielles sous contrainte. A mesure que la durée des missions spatiales augmente et les distances s'agrandissent depuis la planète Terre, il est plus que nécessaire de trouver des moyens d'action pour maintenir, voire améliorer, dans le respect du fonctionnement physiologique, la santé et les performances des futurs équipages. Ces dernières années, la VNS, via taVNS, est au cœur de nombreuses recherches scientifiques en ce qu'elle permet une stimulation non invasive du nerf vague. La littérature a pu souligner son potentiel dans nombre de domaines cliniques, que ce soit dans le traitement de nombreuses pathologies (e.g., psychiques, développementales, neurologiques, métaboliques, cardiovasculaires, gastro-intestinales), pour favoriser l'apprentissage et améliorer les performances ou pour permettre une récupération efficiente. La littérature a également montré que la taVNS augmente l'intéroception en activant les circuits neuronaux qui médient les afférences intéroceptives. Malgré des données prometteuses, l'ensemble des études disponibles mettent en évidence de nombreuses difficultés méthodologiques parmi lesquelles les plus importantes sont une absence de consensus sur les paramètres optimaux de stimulation vagale et de posologie des interventions. Cette absence de consensus suggère qu'il pourrait être envisageable d'étudier une approche personnalisée de l'utilisation de la taVNS en fonction de l'état physiologique du sujet (e.g., niveau de tonus vagal au repos). De plus, il existe un besoin de valider des biomarqueurs de suivi des effets de la taVNS afin de renforcer la compréhension des processus par lesquelles elle agit. Ce besoin en biomarqueurs concerne le patient mais aussi le sujet neurotypique en situation de stress professionnel dont on connait les impacts négatifs sur la thymie, le sommeil, l'efficacité, et le bien-être. Enfin, par rapport aux contremesures existants pour renforcer le système parasympathique, (e.g., biofeedback cardiaque), l'utilisation de la taVNS pourrait bénéficier d'une meilleure compliance dans son utilisation.

Au regard des données encourageantes pour améliorer l'état de santé, la taVNS est depuis peu discutée pour les équipages pour les LDSE. Par conséquent, il existe un besoin de conduire des études pour mieux appréhender les bénéfices de cette technique dans cette population et leur modalité d'utilisation. Nous en venons l'étude SATE conduite dans la dernière partie de ce travail.

L'étude SATE s'attache à répondre à différents objectifs visant à mieux appréhender les modalités d'utilisation de la taVNS chez le sujet neurotypique : (1) étudier l'impact de la répétition de taVNS sur la cognition, le tonus parasympathique via l'indice vagally mediated (RMSSD), le sommeil, et les variables d'adaptation comparativement à une stimulation taVNS unique ; (2) étudier l'impact de la stimulation taVNS (unique versus répétée) sur les indexes de HRV temporels, fréquentiels et linéaires ; (3) étudier les changements de RMSSD au décours de la taVNS (unique et répétée) comme biomarqueur de l'efficacité ou cours de l'intervention. Elle ambitionne également de répondre à des objectifs cliniques : (1) étudier l'impact de la taVNS sur la qualité du sommeil post-stimulation ; (2) étudier l'association entre les bénéfices parasympathique (RMSSD), de cognition, et de sommeil ; et (3) évaluer l'impact de la taVNS sur les variables d'adaptation psychologiques.

En résumé, cette étude exploratoire a pour objectif d'investiguer l'impact de la taVNS sur le fonctionnement cognitif, psychologique et physiologique incluant la réponse de l'ANS ainsi que les bénéfices du nombre de sessions de stimulation taVNS.

Sur le plan expérimental, nous posons l'hypothèse que, comparativement à la stimulation unique, la session répétée produira les effets les plus importants en termes de performances cognitives, de fonctionnement parasympathique, de sommeil et d'adaptation psychologique. Les indices de HRV associés à un meilleur fonctionnement parasympathique et de flexibilité/adaptabilité devraient s'améliorer sous l'effet de la taVNS, et le RMSSD devrait permettre de servir de biomarqueur à l'efficacité de l'intervention. Sur le plan clinique, nous posons les hypothèses que : (1) la taVNS améliore la qualité du sommeil, (2) que ceux qui améliorent significativement leurs performances cognitives et leur qualité du sommeil sont ceux pour qui la stimulation vagale améliore la qualité du tonus parasympathique, et (3) que la taVNS influence l'adaptation psychologique.



Evaluation of taVNS for Extreme Environments:

An Exploratory Study of Health Benefits and Stress Operability

Soumis[16]

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Abstract

Introduction : Research on transcutaneous vagus nerve stimulation (taVNS) is expanding rapidly, and its modalities constitute a major research challenge. Despite promising data in several domains, all available studies highlight many methodological shortcomings. A growing number of reviews stress the need to validate biomarkers for monitoring effects, in order to enhance our understanding of the processes by which taVNS acts. The heart rate variability (HRV) appears to be a relevant candidate that informs on the autonomic nervous system (ANS). This study aims to investigate the impact of taVNS on cognitive, psychological, and physiological including ANS functioning as well as on the benefits of the number of taVNS sessions.

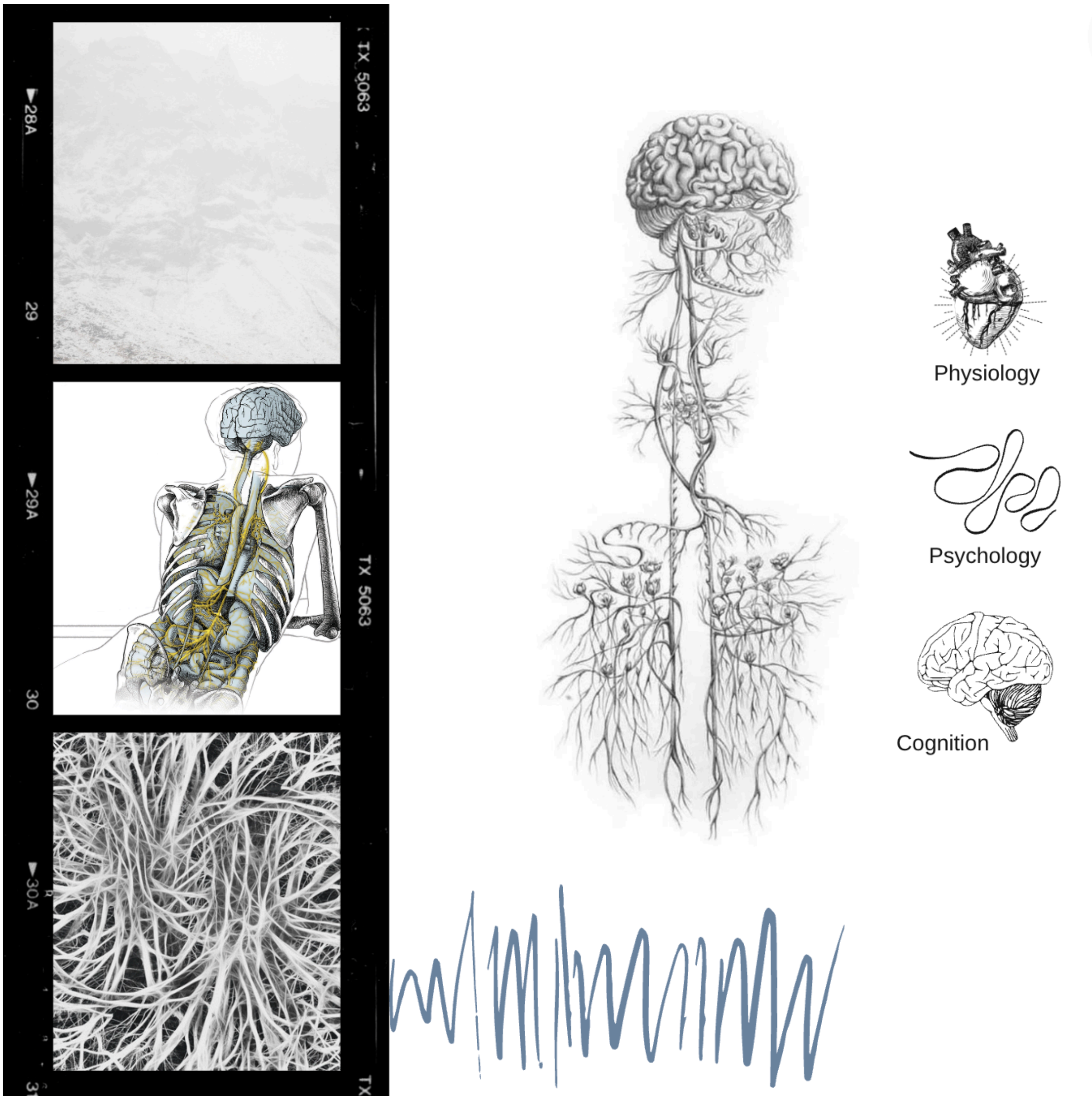
Method: 44 healthy participants were randomly assigned to one of two cross-over protocols: a unique session (one taVNS, one *sham*) or a repeated session (three taVNS, three *sham*). Cognitive, psychological, and physiological measures were performed before (pre) and after (post) each intervention. Sleep monitoring was only recording before the first and after the last intervention in each protocol. Only for the repeated session, participants were allocated to two groups according to their parasympathetic activation gain during the three interventions: high parasympathetic delta (HPd) and low parasympathetic delta (LPd).

Results: Participants in the repeated session increase their HRV, cognitive performance as well as their sleep efficiency. Especially, the taVNS stimulation induced a higher parasympathetic activation and cardiac flexibility compared to the sham in the repeated session. Nevertheless, perception of stress may indicate a nocebo effect of the repeated session. The HPd profile had a higher interoceptive awareness, HRV highlighted by nonlinear measures, cognitive performance, but a decrease in some indicators of sleep efficiency compared to the LPd profile.

Conclusion: The taVNS seems to induce positive health outcomes, especially when the stimulation is repeated three times per a week. Moreover, our findings highlight the benefits of parasympathetic activation during taVNS on psychophysiological and cognitive functioning. Further research is needed to validate these results on a large sample, using longitudinal measures among several months. Finally, this intervention appears promising as a countermeasure to extreme mission and occupations.

Figure 27

Graphical abstract SATE



Keywords

Adaptation, Cognition, Countermeausre, Health, Stress, taVNS

1. Introduction

Space is undergoing a major revolution, with the launch of private enterprise, the first flights by space tourists, and a return to the Moon in the next few years. All these latest achievements have the ultimate goal of enabling human space travel to Mars. Nevertheless, sending humans into space requires an understanding of the effects of microgravity, cosmic radiation, and confinement during the 3-year mission. Far beyond the Van Allen belt, Mars is the most distant destination of all the planets in our solar system, where no human ever thought they would see the color of land. This is no longer a utopia dreamed up in a science fiction book. The ultimate challenge for future research is to explore countermeasures to maintain the adaptive capacities of crews. The importance of the Parasympathetic Nervous System (PNS) tone in stress adaptation, particularly in extreme environments, has been recently demonstrated (1, 2). This activity regulates activation to changes in stress, and its level at rest has been associated with better post-challenge recovery capacities. These findings are part of a body of recent data highlighting the role of high parasympathetic tone in psycho-physio-cognitive adaptation. Increasing parasympathetic tone could therefore be a relevant approach, one means being Vagus Nerve Stimulation (VNS).

1.1. Vagus nerve stimulation

The Vagus Nerve (VN) is the tenth cranial nerve. Anatomically, the VN has an afferent or sensory component and an efferent or motor component, which play an important role in maintaining homeostasis (3–5). The VN leaves the brainstem through the retro-olivary sulcus and the skull through the jugular foramen with nerves IX and XI. Thus, the nerve crosses the neck in the carotid sheath (between the carotid artery and jugular vein), the upper chest along the trachea, the lower chest and diaphragm along the esophagus, and then the abdominal cavity (6). Along the way, its branches innervate various structures such as the larynx, pharynx, heart, lungs, and gastrointestinal tract. In the brainstem, sensory afferent fibers terminate in the nucleus tractus solitarius, which then sends fibers that connect directly or indirectly to various brain regions. These regions include the dorsal raphe nuclei, locus coeruleus, amygdala, hypothalamus, thalamus, and orbitofrontal cortex. The VN fibers can be characterized as three types based on their diameter and myelination, inducing different excitation thresholds in response to a stimulus (7). Type A fibers are the first to be activated, large in diameter and highly myelinated, they have the lowest recruitment threshold (0.02-0.2 mA). Type B fibers are the second to be activated, intermediate in diameter and myelinated, with a medium intensity threshold (0.04-0.6 mA). Type C fibers are the smallest, non-myelinated, and have the highest recruitment threshold (> 2 mA). Several technologies have been developed for stimulating the vagal system. The VNS using an invasive VNS (iVNS) was a revolution for the treatment of drug-refractory epilepsy (1994 in Europe, 1997 in North America), and for treatment-resistant chronic depression (2005). Nevertheless, iVNS requires a costly and invasive surgical procedure involving the implantation of a helical bipolar electrode in the left cervical VN, then connected to a pulse generator, most often placed in a left infraclavicular subcutaneous pocket. Although this procedure can improve the health of many patients, the presence of numerous side effects necessitates a prior benefit/risk assessment (8). Transcutaneous auricular VNS (taVNS) enables non-invasive stimulation of the VN without surgery and avoids the side effects of iVNS. Recently developed, it targets the auricular branch of the vagus nerve (ABVN) skin receptor field in the outer ear. The human outer ear is supplied by three sensory nerves: the auriculotemporal nerve, the great auricular nerve and the ABVN, which provides somatosensory innervation to the outer ear (9). More specifically, two auricular areas have been recognized as targeting the ABVN namely the cymba conchae and the tragus. The study conducted by Peuker and Filler (10) was the first anatomical study to report the complete nerve supply pathway and origin of each auricular branch in 14 human ears. The tragus is 45% innervated by the ABVN, while the cymba conchae has 100% of its fibers originating from the ABVN (10). Other studies using functional magnetic resonance imaging have shown that taVNS induces, unlike sham stimulation, higher activity in the nucleus tractus solitarius, left prefrontal cortex and cingulate areas (11–14). Stimulation parameters for taVNS can differ in terms of current intensity (mA), pulse width (µs), frequency (Hz), duty cycle (s) and session duration (min) (15).

1.2. taVNS benefits across the body

Over the past few years, the literature has demonstrated the beneficial effects of taVNS in a number of domains: psychological disorders (e.g., depression, anxiety, fear, schizophrenia, post-traumatic stress disorder); psychiatrical disorders (e.g., epilepsy, headache, brain injury, stroke, post-stroke rehabilitation); neurodegenerative (e.g., Parkinson's disease, cognitive decline); cognitive (e.g., cognitive disorders, disorders of consciousness); developmental (e.g., psychomotor retardation); genetic (e.g., Prader-Willi syndrome); cardiovascular (e.g., atrial fibrillation, myocardial infarction, heart failure, arrhythmia, tachycardia); chronic diseases (e.g., diabetes, glucose intolerance, chronic pain, obesity, dystonia); gastrointestinal (e.g., gastrointestinal dysfunction, postoperative bowel obstruction, inflammatory bowel disease, colon cancer) or tinnitus treatment (16–18). Furthermore, taVNS improves many psychological functions, including well-being, alertness and cognitive performance, in conjunction with a reduction in negative mood (19), as well as learning (20). Recently, several studies have also highlighted its benefit in the treatment of Covid-19 (21–23). More specifically, taVNS is said to improve sleep quality, particularly in individuals suffering from insomnia (24–27).

1.3. HRV as a biomarker of taVNS effect

The Heart Rate Variability (HRV) has become widely accepted as an objective marker of an individual's response (28–30). Currently, the literature emphasizes the role of parasympathetic activity as a brake on stress (31–35). Porges (36) noted that HRV reflects both chronic stress and vulnerability to stress. Environmental responses are consistent with changes in activity in the sympathetic, parasympathetic, and enteric components of the visceral motor system that govern smooth muscle, cardiac muscle and glands. These systems play a major role in sympathovagal balance and, therefore, contribute to the maintenance of adaptive homeostasis with interindividual differences (35). Thus, variation in HRV may reflect the body's and mind's resistance to a psychological or physical stressor. The cardiac biosignals could be an index of the heart's adaptability to changing environmental conditions. This balance has mainly been assessed by short-term temporal measurements, based on the variation between each consecutive heartbeat. Especially those reflecting rapid beat-to-beat changes, such as root mean square of successive differences (RMSSD) and the percentage of successive normal sinus RR intervals separated by more than 50 ms (pNN50), have been shown to be reliable indices of parasympathetic vagal modulation (37, 38). Moreover, high-frequency power (HF, 0.15-0.40 Hz) reflects vagal-mediated HRV in the frequency domain when respiratory rate is between 9 and 24 cycles per minute (39). Thus, variation in HRV may reflect the body's and mind's resistance to a psychological or physical stressor, and cardiac biosignals could be an index of the heart's adaptability to changing environmental conditions that may be relevant for studying taVNS mechanisms.

1.4. Cognitive influence on adaptation

Cardiac vagal activity would also constitute a measure of the efficiency of an individual's executive functioning. Recently, a new neurocognitive test was developed and named « MindPulse » (40). The purpose of this test is to highlight the elements underlying perceptual-motor decision-making, in particular attentional and executive functions. More generally, this would enable an assessment of an individual's decision-making abilities. These are essential in many areas of everyday life, as well as for crews working in extreme environments. The balance between speed and precision in perceptual-motor decision-making is at stake in adaptation to a potentially changing environment (41). Decision-making is a fundamental adaptive process that enables an individual to choose one of several options (42, 43). The most advantageous option in the short and medium term remains the goal. This neurobiological process involves several cognitive, affective and motivational functions associated with the activation of brain networks that rely on coordinated brain structures, among which the prefrontal cortex, amygdala, insula and nucleus accumbens play key roles (44, 45). This also depends on the context in which individuals find themselves and their own internal needs and feelings (46). The influence of the individual's affective state on decision-making has been explored notably by somatic marker theory (47). Somatic markers and the environment influence the speed of decision-making processes (46). In addition, the combination of an individual's emotional, motivational, and cognitive state, as well as characteristics specific to the environment, are the elements that enable an individual to choose one option over another more quickly (48, 49). These abilities are particularly sensitive to sleep deprivation (50, 42). They appear to be particularly affected in astronauts on space missions. Studies report a decrease in problem-solving ability, attention, memory (i.e., working, short-term and spatial), learning, attention and reaction times (51–57). These changes appear to be linked to sleep deprivation, and circadian desynchronization problems faced by astronauts, as well as to stressors inherent in the environment, notably monotony (58–61). Decision-making is therefore the result of an interplay between different processes that may imply the vagal mind-body axis functioning.

1.5. Objectives of the study

Despite these promising data, the available studies highlight the existence of significant methodological shortcomings. The most important of these are the absence of consensus on optimal parameters for vagal stimulation, intervention posology and heterogeneity between clinical studies. A growing number of reviews emphasizes the importance of validating biomarkers for taVNS monitoring effects to enhance our understanding of the processes involved in taVNS. These needs concern not only the patient, but also the healthy subject under occupational stress, whose complaints in relation to thymia, sleep, efficiency and well-being currently still have too few validated clinical responses. In particular, the restorative value of sleep has received little attention in the benefits of taVNS.

The issue of session repetition raises questions about the optimal number of taVNS sessions for the improvement target. Several studies demonstrate no effect of taVNS on the clinical target studied (62–64). More and more reviews are highlighting the need to use biomarkers in order to strengthen understanding of taVNS efficacy but also to move towards a consensus methodology for taVNS use (15, 65–69). The article by Farmer et al. published in 2020 aims to provide recommendations for future studies (70).

Therefore, this study aims to investigate the impact of taVNS on the quality of cognitive adaptation, parasympathetic tone, and sleep quality. An additional aim is to compare the benefits of a unique sessions with the application of a repeated session. In light of the available literature on the optimal number of sessions (71–75), the focus is on three sessions over a week (74) to study the impact of repeating taVNS compared with a unique taVNS session. Thus, this study proposes the following objectives: (1) to evaluate the impact of taVNS versus sham intervention in the repeated sessions on cognitive (principal criteria) and physiological functioning compared to an unique session ; (2) to evaluate the impact of repeated sessions on sleep quality compared to unique session ; (3) to evaluate the impact of taVNS versus sham intervention on psychological functioning among the repeated sessions ; (4) to evaluate RMSSD modifications during repeated taVNS intervention as a biomarker of efficacity.

2. Materials & methods

2.1. Design

The present study (ID-RCB: 2022-A02512-41) was approved by the Committee for the Protection of Individuals (CPP Nord Ouest I, Rouen, France) and was conducted according to the standards of the Declaration of Helsinki. After comprehensive verbal and written presentations, all participants gave their written consent to participate.

2.2. Participants

44 healthy subjects (24 women and 20 men) were recruited for this study. Their health status was confirmed by a clinical history.

Demographics are given as mean ± standard deviation. Mean age was 30.09 ± 5.11 years (ranging from 24 to 43). Among the 24 women, five (20.83%) was using contraception (i.e., contraceptive pill). Only ten of the participants were smokers (22.72%) and five were taking treatments for hypertension, iron supplementation, salbutamol, and antihistamines. 19 participants had a medical history including minor surgery, ear infections, tympanic perforation, salivary gland infection. Average height was 172.56 ± 7.72 centimeters, and weight 68.90 ± 12.12 kg.

Among subjects, 25 participants were single (56.81%), 19 were in couple (43.18%) in which one has a child (2.27%). 37 (84.09%) reported that they encountered major personnel and 32 (72.72%) professional stressful events. One (2.27%) finished high school, 10 (22.72%) have a bachelor, 25 have a master's degree (56.81%), and 8 (18.18%) have a PhD.

Table 1 reports sociodemographic characteristics.

Table 1

Socio-demographic characteristics of participants

Measurements	Data*
N	44
Mage	30.09 ± 5.11
Mheight	172.56 ± 7.72
Mweight	68.90 ± 12.12
Gender (women - men)	54.54% - 45.45%
Single	56.81%
In couple - with children	43.18% - 2.27%
Contraception	20.83%
Smoker	22.72%
Major personal stressful events	3.81 ± 4.00
Major professional stressful events	2.06 ± 2.57
Level of education (High school - Licence - Master - PhD)	2.27% - 22.72% - 59.09% - 18.18%

*Mean and standard deviation are reported when relevant. Other figures show the ratio of the number of subjects.

2.3. Inclusion and exclusion criteria

Inclusion criteria included: (1) aged between 24 and 40 years old; (2) no anxiety and depressive disorders assessed by the Hospital Anxiety and Depression scale (HAD, Zigmond & Snaith, 1983) ; (3) no history of head trauma ; (4) absence of metallic implant, (5) no recent ear trauma, (6) no facial or ear pain.

Exclusion criteria included: (1) no endocrinal pathology or treatment (e.g., hyperthyroidism, diabetes, hypertension, sex reassignment) ; (2) pregnancy, and breastfeeding ; (3) anti-inflammatory treatment ; (4) treatments interfering with heart rate (e.g. beta-blockers, calcium channel blockers, $\alpha 1$ receptor agonists) ; (5) psychotropic treatment ; (6) psychiatric or psychic disorders ; (7) cardiovascular disorders ; (8) alcohol dependance ; (9) recent use of illicit drugs ; (10) active implantable device (e.g. pacemaker) ; (11) personal or family history of epileptic seizures ; (12) persons deprived of their liberty, persons hospitalized without consent, persons admitted to a health or social institution for purposes other than research (L-

1121-5 to L-1121-8-1 ; (13) minors (under 18 years old) ; (14) protected adults, adults unable to express their consent who are not under protective supervision.

2.4. Experimental design

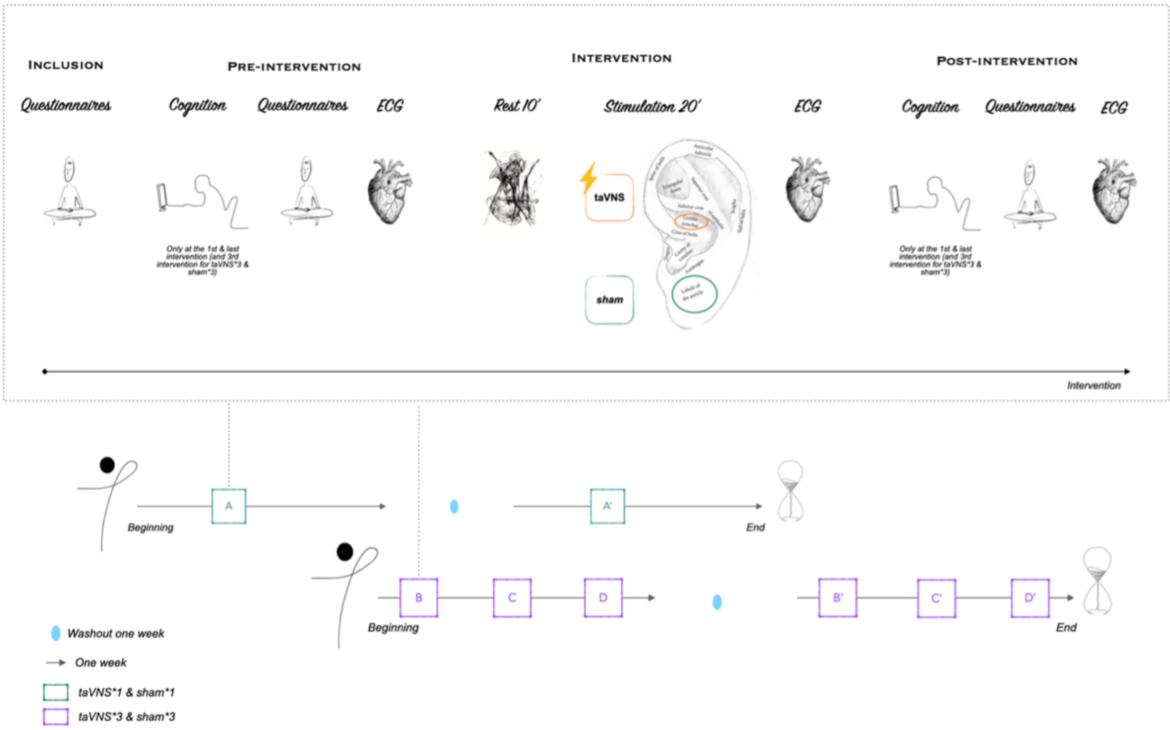
The experimentation took place at the Hôtel Dieu Hospital (Paris, France) in June and July 2023. This is a single-center, cross-over, interventional, exploratory study to evaluate the potential of taVNS on cognitive and psychophysiological functioning. Participants were randomized into two cross over protocols:

- Unique session (n = 22): two interventions composed of one taVNS (A, taVNS*1) and one sham per week (A', *sham**1).
- Repeated session (n = 22): six interventions composed of three taVNS (B, C, D, taVNS*3) and three sham per week (B', C', D', *sham**3), scheduled every two or three days.

For each protocol, two stimulations were administered in a randomized order to compare the effects of within-subject vagal stimulation: taVNS (active) and *sham* (control); sham (control) and taVNS (active). Thus, depending on the randomization group, subjects started with either the taVNS or *sham* condition.

A washout period between each condition was one weeks, whatever the protocol (Figure 1).

Figure 1
Overview of the experimental design



Cognitive, psychological, and physiological data were assessed at each intervention, before (pre intervention) and after (post intervention) the stimulation protocol (i.e., taVNS or *sham*), except for the repeated session (taVNS*3, *sham*3) in which the cognitive test was performed twice during the first and the third intervention.

Sleep stages were monitored the night before the first intervention and the night after the last intervention for the repeated sessions. Sleep diaries were completed on the same time period.

2.5. Data collection

A 15-item sociodemographic questionnaire was developed to collect general information on the participant's family situation, medical history, current health status, and hobbies.

2.5.1. Psychological measurements

A 32-item Multidimensional Assessment of Interoceptive Awareness (MAIA) questionnaire evaluates interoceptive awareness. The scale is divided into eight sub-factors that measure awareness of uncomfortable, comfortable, and neutral body sensations, the response to sensations of pain and discomfort, the ability to regulate attention to body sensations, and awareness of mind-body integration (i.e., noticing, not distracting, not worrying, attention regulation, emotional awareness, self-regulation, body listening, trusting) (76).

A 14-item Perceived Stress Scale (PSS) assesses the subjective stress level (77).

2.5.2. Cognition measurements

Cognitive performance was evaluated using the MindPulse test, developed by Suarez et al. (40), which assesses decision-making. Subjects are seated in front of a computer screen that shows images requiring a response (instructions are displayed on the screen). The test battery consists of three tests of increasing complexity. Each test begins with a learning phase consisting of four trials, followed by a test phase. Different image packages are used for learning and test phases. Each image is presented only once to avoid any learning effect.

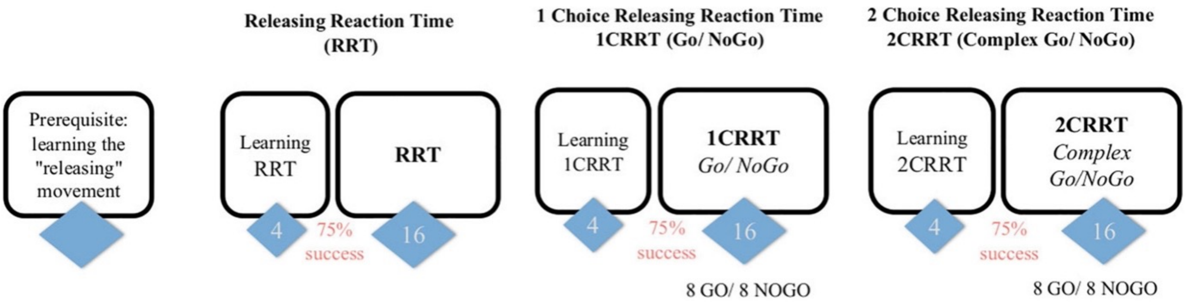
The first test consists of a *Releasing Reaction Time Task* (RRT). The participant is prompted to click down on a mouse button and must maintain the pressure until a stimulus (an image is presented in the center of the screen on a white background) appears. At this point, the button is released. Then the screen remains blank for between 2 and 7 seconds before another prompt appears to press down on the mouse button. When a new image is shown on the screen, the mouse must be released as fast as possible. The participant may practice as many times as necessary.

The second *1 Choice Releasing Reaction Time* (1CRRT) test consists of a Go/No-Go task. Here, the participant is instructed to only respond immediately (release the mouse button) to images of a certain color (white or gray, chosen randomly at the beginning of the test). If the image does not satisfy the color criteria, the subject maintains the pressure until prompted to release the button (after 3 seconds). The third, *2 Choice Releasing*

Reaction Time (2CRRT) test also consists of a Go/No-Go task. In this case, the participant must only respond to an image that meets two criteria (the other color from the 1-choice task, and an animate or inanimate object, chosen randomly).

The computer records Reaction Time (RT) and response quality (the number and type of errors) for each trial. RT is divided into three main components: Simple Reaction Time (SRT), Executive Speed (ES), and Reaction to Difficulty (RD). Figure 2 presents an overview of the MindPulse battery of tests.

Figure 2
Overview of the MindPulse test battery



2.5.3. Physiological measurements

Sleep monitoring. Sleep stages were recorded using a DREEM v2 Headband. The device records: the total recording time (TRT), total sleep time (TST), sleep onset latency (SOL), he wake after sleep (WASO), total awake time during recording (WAKE), minutes of N1 sleep stages (N1 min), minutes of N2 sleep stages (N2 min), minutes of N3 sleep stages (N3 min), minutes of non-rapid eyes movement sleep stages (NREM min), minutes of rapid eyes movement sleep stages (REM min), percentage of TST in N1 sleep stages (N1%), percentage of TST in N2 sleep stages (N2%), percentage of TST in N3 sleep stages (N3%), percentage of TST in NREM sleep stages (NREM%), percentage of TST in REM sleep stages (REM%), sleep efficiency (SE), sleep onset (SO), latency to persistent sleep (LPS), mean respiration rate during the night (RRm), mean respiration rate during WAKE epochs (RR WAKE), mean respiration rate during N1 epochs (RR N1), mean respiration rate during N2 epochs (RR N2), mean respiration rate during N3 epochs (RR N3), mean respiration rate during REM epochs (RR REM).

HRV. Heartbeat interval data (RR) were recorded using the gold standard ECG data in an integrated system and software package (Biopac MP160 System Inc., California, USA) at a sampling frequency of 2000 Hz. Each participant wore 3-lead ECG (BN-EL45-LEADS3) configuration placed on the right chest, the left chest, and the lower left chest. An alcohol pad was used to remove the top layer of dead skin cells. Three self-adhesive disposable electrodes (2.5 cm × 2.5 cm) were placed on the above-mentioned areas. Electrodes were connected to a Biopac BIONOMADIX ECG2-R. The positive lead was attached to the left chest electrode; the negative lead was attached to the right chest electrode (Lead II derivation); the ground electrode was attached to the lower left chest. RR data were recorded for a ten-minute period in a sitting position at each intervention, except during the first and the last intervention in which a 10-minute period in a standing position was added.

The HRV analysis followed guidelines reported in (39, 78), which take into account potential circadian variation, and used the *PyHRV* python library (79). The following data were recorded: weight; height; waist-to-hip ratio; smoking habits; most recent alcohol intake (>24h); most recent caffeinated (coffee/tea) intake (>2h); most recent meal (>2h); most recent physical activity (>24h); and quality of sleep on the day of the experiment and the preceding day.

Raw ECG data were filtered between 3 and 45 Hz using a finite impulse response band-pass filter. The order of the filter was set at 600 (0.3 times the sampling frequency). R peaks were automatically detected using the *BioSPPy* python library (80). A Hamilton segmentation was performed on the filtered signal, followed by R-peak correction with tolerance set to 0.05. R-waves were manually examined to ensure correct detection. If an ECG sequence was overly noisy when visualizing the superposition of all QRS complex, the time interval was manually removed to improve data quality. RR intervals were automatically detected with the *hrvanalysis* module using linear interpolation, and manually corrected for artifacts and ectopic beats.

Time domain analysis. Time domain HRV metrics included mean HR (the mean Heart Rate), RR (the mean interbeat interval), SDNN (Standard Deviation of the Normal-to-Normal RR interval), RMSSD (Root Mean Square of Successive Differences between adjacent RR intervals), and pNN50 (percentage of adjacent NN intervals that differ from each other by more than 50 ms).

Frequency domain analysis. Frequency domain HRV metrics complemented time domain metrics and included oscillatory components of heart rate dynamics. Spectral density was estimated using Welch's method: low frequencies (i.e., sympathetic and parasympathetic activity) in the range 0.04–0.15 Hz, and high frequencies (i.e., parasympathetic activity) in the range 0.15–0.4 Hz.

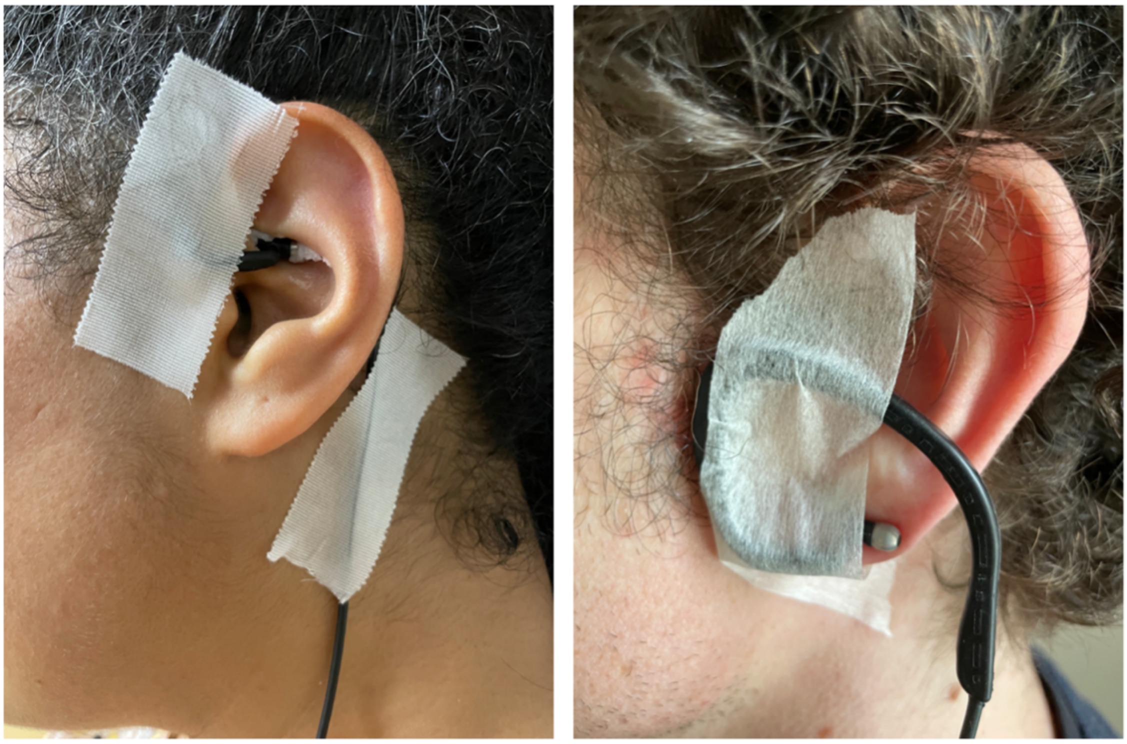
Nonlinear analysis. Nonlinear HRV metrics reflect dynamic and chaotic internal states that other metrics cannot reflect. The most representative metrics were used: the poincaré plot (i.e., graphical representation of the correlation between successive interbeat intervals), SD1 (Standard Deviation of instantaneous interbeat interval variability), SD2 (Standard Deviation of continuous, long-term RR variability), α1 (detrended fluctuation analysis self-similarity parameter that represented short-term fluctuations), α2 (detrended fluctuation analysis self-similarity parameter that represented long-term fluctuations), sample entropy (i.e., regularity and complexity of time series).

2.6. Intervention

Whatever the *sham* or taVNS stimulation, the subject's ear was inspected to ensure that the area is free of wounds and jewelry. The experimenter confirmed with the subject that there are no skin-related contraindications at the stimulation site, including sunburn, cuts, lesions, or open wounds. An alcohol preparation pad (70% isopropyl alcohol) was used to gently rub the target site, both internally and externally, to decrease skin resistance and increase conductance. The electrodes of the tVNS® L device (tVNS Technologies, Germany) were positioned in the left ear (i.e., even if no the literature did not reveal no contraindication to lateral stimulation, see Farmer et al., (70) for a review and recommendations), at the level of the cymba conchae in the taVNS condition or turned upside down and placed at the level of the earlobe in the *sham* condition (i.e., the earlobe is supposed to be free of vagal innervation). White medical adhesive tape was used to secure the electrodes in place (Figure 3). The experimenter ensured that this was not uncomfortable.

Figure 3

Position of the tVNS L device in the taVNS (left) or sham condition (right)



The stimulation protocol then began. The experimenter explained that subjects would randomly feel an input in their ear, and that two different protocols would be applied depending on how they felt: (1) they feel nothing (*sham*), in which case they remain seated for 20 minutes in a half-seated position; (2) they feel a sensory input (taVNS), in which case the perceptual threshold is determined before remaining seated for 20 minutes in a half-seated position. In order to determine the perception threshold, 5-second stimulation trials were applied, starting at 0.1 mA and increasing with each trial by 0.2 mA. Participants rated their current sensation (« How intense is the pain induced by the stimulation? »), ranging from 0 (« no sensation at all ») to 10 (« the strongest sensation imaginable »), until stabilizing at around 5 (« slight stinging »). In practice, in the event of a « stinging » or « tickling » sensation, the stimulation intensity was reduced by 50% and the previous step was repeated. If not, the stimulation intensity was increased by 50% and the initial step repeated until a minimum of 4 « yes » responses to the « prickly » or « tickling » sensation are recorded. The intensity (in mA) applied was the value at which the subject says their fourth « yes » response after saying « no » (81, 70).

Accordingly, electrical stimulation was applied to the subject's left ear via a titanium electrode placed at the level of the cymba conchae in the taVNS condition, or using the same electrode turned upside down and placed at the level of the earlobe in the *sham* condition. In the taVNS condition, parameters are predefined with a frequency of 25 Hz, pulse widths between 200-300µs and alternating intervals of 30 s stimulation ON and 30 s OFF. In the *sham* condition, no stimulation was delivered. At the same time of the intervention, an ECG (MP160, Biopac) was recorded to assess its implication as a biomarker of the response to vagal stimulation. After both the taVNS or *sham* conditions, the experimenter inspected the ear for any redness or irritation at the stimulation site and note any observations.

2.7. Statistical methods

Statistics were computed for all outcome measures. Data analyses were performed with JASP (Amsterdam, version 0.16.3), an open-source software package that is used for both classical and Bayesian analyses. Descriptive statistics were expressed as mean ± SD. The Shapiro–Wilk test was used to determine whether data were normally distributed. When the analysis was significant, effect sizes were reported.

To compare the unique and repeated sessions, deltas between the first and the last *sham* and taVNS stimulation were calculated for each cognitive psychological, and physiological variable. ANOVA two-way or Kruskal-Wallis signed rank analyses were used according to the normal distribution to evaluate the impact of the intervention (i.e., *sham* and taVNS) and session (i.e., unique and repeat) on cognitive and physiological delta. Similar analyses' strategies were used to evaluate the impact of time (i.e., pre intervention and post intervention) and intervention (i.e., *sham* and taVNS) on the sleep monitoring. In order to explore the impact of the intervention of perceived subjective stress among the repeated session, we used repeated-measures ANOVA.

To evaluate RMSSD modifications during repeated taVNS, the mean of the three values of RMSSD recording during taVNS intervention was used to calculate a delta between the mean of RMSSD and RMSSD of the 1st pre intervention. The median (= 11.43) was used to differentiate our population on the RMSSD delta. Thus, we elaborated two profiles based on the parasympathetic gain during taVNS compared to before the first intervention. The first one, the high parasympathetic delta (HPd) have the most parasympathetic activation during taVNS intervention and the second one, the low parasympathetic delta (LPd) have the lowest parasympathetic activation during the taVNS intervention. Following the establishment of parasympathetic profiles, repeated-measures ANOVA were used to evaluate the impact of parasympathetic activation profiles during taVNS on cognitive, psychological, , and physiological functioning.

Holm *post hoc* analyses were performed when the *p*-value was significant. Bayesian analyses were performed, by applying equivalent analyses for ANOVA analyses. The Bayesian Factor was calculated if no significant effect was detected. A low value is understood as supporting the null hypothesis, and a high value indicates evidence in favor of the alternative hypothesis (Supplementary Materials). For all analyses, statistical significance was set at $p < .05$. A *p*-value between .05 and .07 was considered as evidence of a trend.

3. Results

3.1. Cognition and physiological functioning among unique vs. repeated sessions

Cognition. A trend to session effects were found for the simple reaction time dispersion [F (1,84) = 3.515, $p = .064$, $w^2 = .028$] as well as for outliers' answers [F (1,84) = 3.240, $p = .075$, $\eta^2 = .037$].

Participants in the repeated session had a higher simple reaction time dispersion but lower outliers' answers than those in the unique session.

HRV. A significant session effect was found for HR [F (1,84) = 4.371, $p = .042$, $w^2 = .036$]. A significant session*intervention effect was found for SDNN [F (1,84) = 6.203, $p = .015$, $\eta^2 = .067$], RMSSD [F (1,84) = 6.261, $p = .014$, $\eta^2 = .068$], HF [F (1,84) = 3.872, $p = .052$, $\eta^2 = .043$], SD1 [F (1,84) = 6.251, $p = .014$, $\eta^2 = .068$] as well as SD2 [F (1,84) = 5.758, $p = .019$, $\eta^2 = .062$]. A trend for a significant session effect was found for RR interval [F (1,84) = 3.487, $p = .065$, $\eta^2 = .038$].

Post hoc analyses revealed that participants in the repeated session had a higher RMSSD ($p = .035$), HF ($p = .052$), SD1 ($p = .035$) in taVNS condition compared to sham condition. Participants of the sham condition had a higher SDNN ($p = .025$) and a lower

SD2 (p = .027) in the repeated session compared to those in the unique session. Moreover, subjects in the repeated intervention had a higher HR and tend to have lower RR intervals compared to those in the unique intervention.

Tables 2 presents a summary of the cognitive and physiological differences among interventions.

Table 2

Cognition and physiological functioning delta among unique vs. repeated sessions

	Unique		Repeated		*p*-value*
	taVNS	sham	taVNS	sham	
HRV					
HR[a]	-2.901 ± 5.136	-2.939 ± 4.017	-2.111 ± 7.765	2.398 ± 9.280	.042
NNI[a]	30.373 ± 60.956	29.156 ± 46.646	23.752 ± 85.643	-21.404 ± 86.036	.065
SDNN[b]	4.213 ± 11.115	9.620 ± 14.397	6.878 ± 17.213	-2.330 ± 11.419	.015
RMSSD[b]	1.066 ± 7.167	3.332 ± 8.789	5.249 ± 12.259	-2.792 ± 9.714	.014
HF[b]	32.372 ± 278.665	54.022 ± 333.106	175.406 ± 479.151	-146.002 ± 500.439	.043
SD1[b]	.754 ± 5.068	2.356 ± 6.215	3.712 ± 8.668	-1.974 ± 6.868	.014
SD2[b]	5.827 ± 15.710	13.431 ± 19.643	8.884 ± 23.674	-2.907 ± 15.622	.019
Cognition					
SRTd[a]	-4.000 ± 5.676	7.857 ± 15.774	-2.500 ± 7.546	12.143 ± 17.043	.064
OAa	.318 ± 1.041	.322 ± 1.040	.000 ± 1.380	-.227 ± 1.020	.075

Note. HR = mean heart rate; NNI = mean of successive RR intervals; SDNN = standard deviation of the normal-to-normal RR interval; RMSSD = root mean square of successive Ddfferences between adjacent RR intervals; HF = high frequency; SD1 = standard deviation of short-term RR variability; SD2 = standard deviation of long-term RR variability; SRTd = simple reaction time dispersion; OA = outliers answers.

*p-value used in the analysis of effects. Means and standard deviations are shown for each variable. Only significant interactions were reported (p <.05).

[a] Significant session (unique or repeated) effect.

[b] Significant session*intervention effect.

[c] Significant intervention (taVNS or sham) effect.

3.2. Exploration pf psychological and physiological functioning among repeated sessions

3.2.1. Sleep measurements among repeated sessions

Sleep monitoring. Significant time*intervention effects were found for the TRT [F (1,38) = 1.938, p = .013, η^2 = .137], TST [F (1,38) = 7.018, p = .012, η^2 = .142], NREM (min) [F (1,38) = 3.892, p = .056, η^2 = .084], LPS [F (1,38) = 6.520, p = .015, η^2 = .143]. A trend to a time*intervention effect was found for the WASO [F (1,38) = 3.716, p = .061, η^2 = .083].

Post hoc analyses revealed that participants in the repeated session who received the taVNS decreased their TRT (p = .022), TST (p = .028) post compared to pre interventions. They also decreased their TRT (p = .036), TST (p = .030) post interventions compared to the sham condition. Participants who received the taVNS tended to decrease their WASO (p = .068), NREM (min) (p = .062), LPS (p = .072) compared to those who received the sham post interventions.

Tables 3 presents a summary of the sleep monitoring differences among interventions.

Table 3

Sleep monitoring accros time among unique vs. repeated sessions

	Pre intervention		Post intervention		*p*-value*
	taVNS	sham	taVNS	sham	
Unique session					
NREM[a] (%)	75.364 ± 5.278	76.091 ± 5.278	72.909 ± 4.721	71.636 ± 6.407	.044
REM[a] (min)	102.409 ± 34.315	87.727 ± 31.270	115.182 ± 34.035	113.955 ± 35.424	.063
Repeated session					
TRT[b]	.311 ± .048	.295 ± .065	.240 ± .070	.317 ± .041	.013
TST[b]	403.750 ± 72.243	372.636 ± 80.379	296.545 ± 108.946	402.350 ± 62.868	.012
WASO[b]	25.250 ± 13.273	23.909 ± 16.386	11.909 ± 8.068	31.250 ± 26.944	.061
NREM[b] (min)	290.800 ± 58.147	284.636 ± 60.368	217.227 ± 102.196	298.650 ± 52.532	.056
LPS[b]	20.150 ± 9.551	31.955 ± 24.891	42.591 ± 40.111	15.150 ± 6.708	.015

Note. NREM (%) = percentage of non-rapid eyes movement sleep stages; REM (min) = rapid eyes movement sleep stages in minutes; TRT = total recording time; TST = total sleep time; WASO = wake after sleep onset; NREM (min) = minutes of non-rapid eyes movement sleep stage; LPS = latency to persistent sleep.

*p-value used in the analysis of effects. Means and standard deviations are shown for each variable. Only significant interactions were reported (p <.05).

[a] Significant session (unique or repeated) effect.

[b] Significant session*intervention effect.

[c] Significant intervention (taVNS or sham) effect.

3.2.2. Impact of interventions on perception of stress across time

Subjective stress. There was a significant effect of time [F (5,210) = 2.921, $p = .014$, $\eta^2 = .046$], a significant effect of time*intervention [F (5,210) = 2.347, $p = .042$, $\eta^2 = .037$] and a significant intervention effect [F (1,42) = 7.964, $p = .007$, $\eta^2 = .040$] on perceived stress.

Post hoc analyses revealed that participants perceived more subjective stress post 2nd intervention compared to pre 1st intervention ($p = .005$). At post 1st intervention, those who received the taVNS had a higher perception of stress compared to the sham ($p = .044$). Similar other results were found. At post 2nd intervention, participants who received the sham had lower level of subjective stress compared to the taVNS at pre ($p = .017$) and post ($p = .005$) 1st interventions, pre 2nd intervention ($p = .030$). Also, those who received the sham tended to have a higher perception of subjective stress at post 3rd intervention compared to post 2nd intervention ($p = .074$). Moreover, participants who received the taVNS had a higher perception of stress than the sham intervention.

Tables 4 presents a summary of the stress perception differences among interventions.

Table 4

Stress perception accros time among repeated sessions

	Pre 1st intervention		Post 1st intervention		Pre 2nd intervention		Post 2nd intervention		Pre 3rd intervention		Post 3rd intervention		*p*-value*
	taVNS	sham	taVNS	sham	taVNS	sham	taVNS	sham	taVNS	sham	taVNS	sham	
PSS													
Subjective stress[a,b,c]	24.318 ± 8.097	22.636 ± 7.594	25.045 ± 6.973	17.045 ± 6.862	23.955 ± 9.110	19.045 ± 7.061	19.773 ± 9.690	15.682 ± 6.736	23.091 ± 8.411	20.318 ±6.743	20.818 ± 8.410	23.000 ± 6.218	.042

Note. PSS = perceived stress scale.

*p-value used in the analysis of effects. Means and standard deviations are shown for each variable. Only significant interactions were reported (p <.05).

[a] Significant session (unique or repeated) effect.

[b] Significant session*intervention effect.

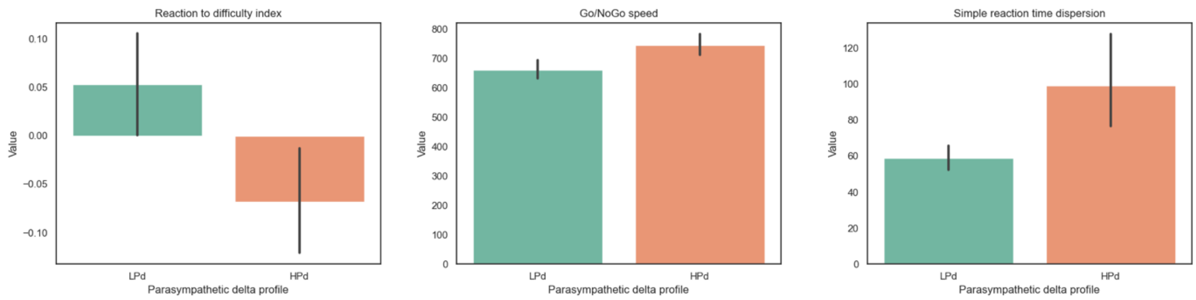
[c] Significant intervention (taVNS or sham) effect.

3.2.3. Impact of parasympathetic activation during taVNS

Cognition. Significant intervention effects were found for reaction to difficulty index [F (1,20) = 5.538, p = .029, η^2 = .097], Go/NoGo speed [F (1,20) = 4.521, p = .046, η^2 = .123], and a trend for the simple reaction time dispersion [F (1,20) = 3.797, p = .066, η^2 = .077].

The HPd profile had a lower reaction to difficulty index and a higher Go/NoGo speed than the LPd profile. The HPd profile tended to have a higher simple reaction time dispersion than the LPd profile (Figure 4).

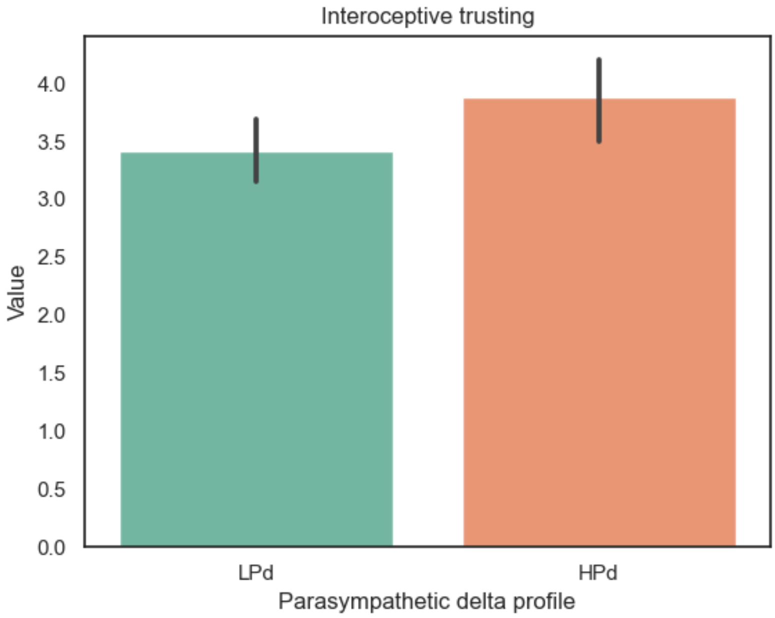
Figure 4
Cognitive performance among profiles



Interoception. A significant intervention group effect [F (1,20) = 6.834, p = .017, η^2 = .060] was found for trusting.

The HPd profile had a higher interoceptive trusting compared to the LPd profile (Figure 5).

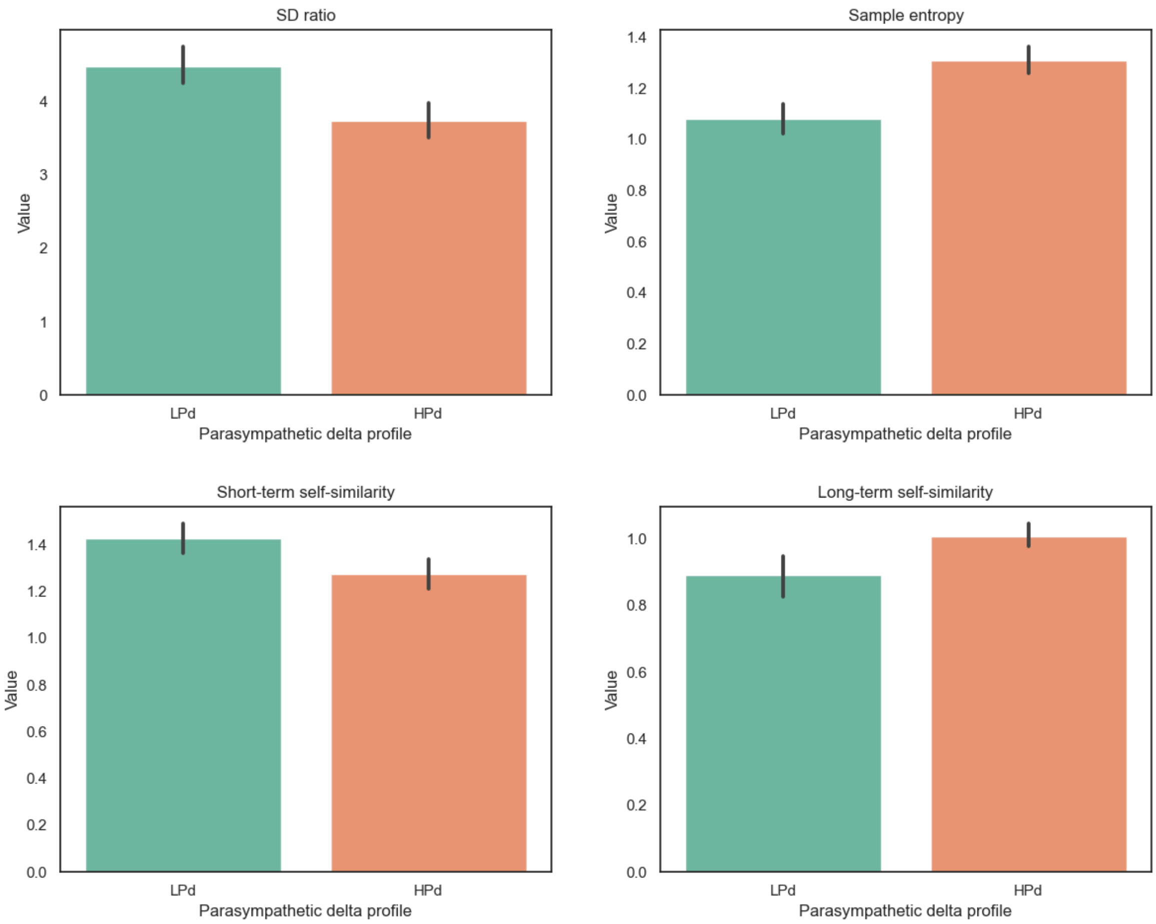
Figure 5
Interoceptive trusting among profiles



HRV. There were significant intervention group effects for SD ratio [F (1,20) = 4.577, p = .045, η^2 = .121], α1 [F (1,20) = 5.833, p = .025, η^2 = .167], α2 [F (1,20) = 4.796, p = .041, η^2 = .148], SampEn [F (1,20) = 9.209, p = .007, η^2 = .194].

The HPd profile had a lower SD ratio, α1 as well as a higher α2 and SampEn compared to the LPd profile (Figure 6).

Figure 6
Nonlinear HRV indices among profiles



Sleep monitoring. Significant intervention effects were found for WAKE [F (1,19) = 5.043, p = .037, η^2 = .210] and a trend for RR N1 [F (1,19) = 3.471, p = .078, η^2 = .154].

The HPd profile had a higher total awake time during recording and tended to have a higher respiration rate during N1 epochs than the LPd profile (Figure 7).

Figure 7
Sleep quality among profiles

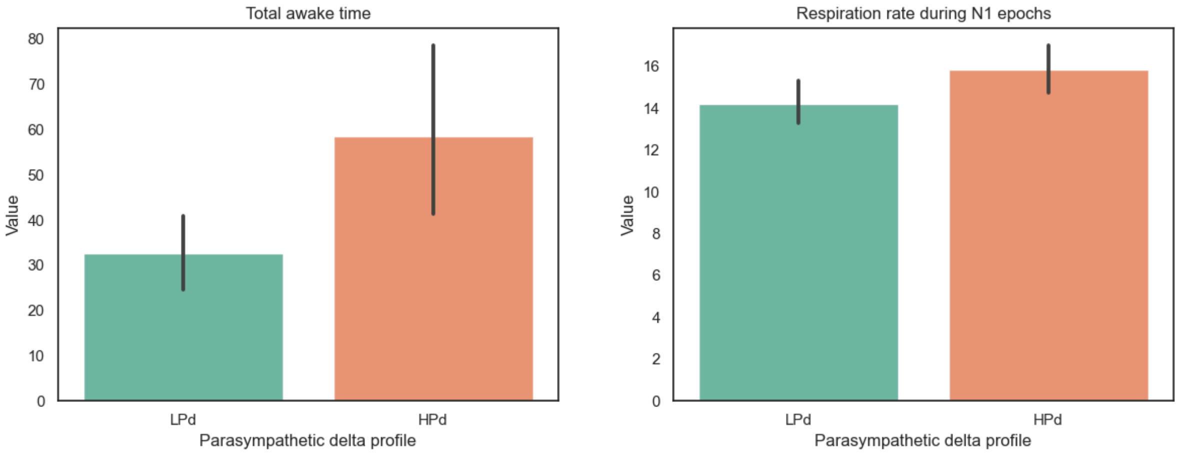


Table 5 and 6 present the impact of parasympathetic activation during taVNS on psychophysiological and sleep functioning.

Table 5

Impact of parasympathetic activation during taVNS on psychophysiological functioning

	Pre 1st intervention		Post 1st intervention		Pre 2nd intervention		Post 2nd intervention		Pre 3rd intervention		Post 3rd intervention		*p*-value*
	HPd	LPd	HPd	LPd			HPd	LPd			HPd	LPd	
MAIA													
Trusting			4.306 ± .559	3.500 ± .741			4.083 ± .780	3.567 ± .876			3.278 ± 1.399	3.200 ± .773	.017
Cognition													
RD	-1.114 ± .200	.071 ± .155	-.058 ± .135	.077 ± .180					-.058 ± .136	.011 ± .147	-.041 ± .275	.053 ± .239	.029
SRTd	93.331 ± 66.375	54.889 ± 22.909	134.937 ± 161.220	57.920 ± 20.112					76.810 ± 43.061	54.654 ± 17.645	91.238 ± 48.664	68.183 ± 29.598	.066
GnGs	780.242 ± 117.366	664.469 ± 132.060	749.011 ± 100.426	657.154 ± 129.109					711.897 ± 81.515	663.288 ± 82.989	741.144 ± 172.276	657.683 ± 86.093	.046
HRV													
SD ratio	3.863 ± .835	4.387 ± 1.128	3.633 ± 1.084	4.252 ± 1.001	3.687 ± 1.184	4.265 ± .760	3.908 ± 1.238	4.507 ± .895	3.627 ± .692	4.685 ± 1.183	3.697 ± 1.071	4.817 ± 1.208	.045
α1	1.287 ± 220	1.368 ± .272	1.270 ± .230	1.403 ± .231	1.223 ± .241	1.476 ± .160	1.317 ± .246	1.461 ± .174	1.235 ± .124	1.495 ± .187	1.260 ± .192	1.478 ± .156	.025
α2	.984 ± .088	.894 ± .275	1.018 ± .134	.899 ± .231	1.015 ± .136	.874 ± .171	1.013 ± .144	.891 ± .123	1.023 ± .092	.829 ± .233	1.005 ± .158	.840 ± .216	.041
SampEn	1.227 ± .179	1.112 ± .265	1.321 ± .260	1.162 ± .282	1.320 ± .304	1.018 ± .235	1.272 ± .273	1.073 ± .183	1.356 ± .141	1.060 ± .235	1.354 ± .269	1.049 ± .179	.007

Note. MAIA = multidimensional assessment of interoceptive awareness; RD = reaction to difficulty; SRTd = simple reaction time dispersion; GnGs = Go/NoGo speed; HRV = heart rate variability; SD ratio = standard deviation of short-term over long-term RR variability ; α1 = detrended fluctuation analysis self-similarity parameter that represented short-term fluctuations, α2 = detrended fluctuation analysis self-similarity parameter that represented long-term fluctuations; SampEn = sample entropy.

*p-value used in the analysis of effects. Means and standard deviations are shown for each variable. Only significant interactions were reported (p <.05).

Table 6

Impact of parasympathetic activation during taVNS on sleep

	HPd	LPd	*p*-value*
Sleep monitoring			
WAKE	58.500 ± 33.481	32.750 ± 14.438	.037
RR N1	15.839 ± 2.136	14.231 ± 1.779	.078

Note. WAKE = total awake time during recording; RR N1 = mean respiration rate during N1 epochs.

**p*-value used in the analysis of effects. Means and standard deviations are shown for each variable. Only significant interactions were reported (p <.05).

4. Discussion

Although a significant amount of research is still required, taVNS interventions offer a promising outcome in clinical medicine to improve the quality of life. The aims of this study were to investigate the impact of taVNS on the quality of cognitive and psychophysiological functioning as well as to compare the impacts of the number of sessions. Overall, this study shed light on main findings: (1) benefits of three sessions per weeks of taVNS instead of a single session ; (2) positive outcomes of taVNS to improve cognitive, physiological, and psychological functioning as well as sleep quality ; (3) taVNS intervention is not suitable for everyone ; (4) the more parasympathetic functioning is increased during the taVNS stimulation, the greater the health benefits.

4.1. The added value of repeated sessions to improve health

Results reveal two types of responses on the physiology and the cognition. A dose effect of the taVNS stimulation with a higher parasympathetic functioning (RMSSD, HF) and a better flexibility of the cardiac biosignal in the short-term variability compared to the *sham* in case repeated session (i.e., 3 interventions per week). Interestingly, compared to the unique session, the sham had a higher sympathetic activation (SDNN) and a lower flexibility of the cardiac biosignal in the long-term variability. Moreover, altogether participants had a lower HRV in the repeated session compared to those in the unique session. This last result seems to mainly translate the outcomes of the sham intervention instead of the taVNS. In consequence, the repetition of the placebo intervention induces negative HRV effects.

Nevertheless, cognitive performance, especially through the executive functions, is mitigated by the repetition of the interventions. Les fonctions exécutives font références aux processus mentaux descendants qui servent le comportement dirigé vers un but (82).

Thus, even if a higher dispersion of the simple reaction time was observed, participants in the repeated session made lower outliers answers compared to the unique session. A substantial body of empirical evidence exists connecting higher levels of cardiac vagal activity with better executive performance (83, 84). Borges and collaborators (85) conducted a study to examine the effects of taVNS on specific executive functions, including inhibitory control and cognitive flexibility. They highlighted that the expected association between taVNS and executive functions might be understood by considering the neuroanatomical pathways of the vagus nerve. Executive functions and cardiac vagal activity share overlapping neurological structures, both being regulated by cortical areas, notably the prefrontal cortex (86). Given that the taVNS signal is sent afferently to the prefrontal cortex via the ABVN, cardiac vagal activity could be affected by vagal stimulation (87). This hypothesis requires further study to be validated. Another important issue will be to confirm the dispersion of reaction times observed during repeated sessions. This possible instability and stability of reaction times could signal a decline in attentional and/or motivational functions.

In the repeated session, the taVNS stimulation induces a decreased sleep time after the intervention and compared to the sham. Nevertheless, they increased their sleep quality with a decreased WASO, NREM, and LPS. The literature among insomnia patients highlighted the use of taVNS to improve sleep (88, 89). Although a previous study shows a decrease of REM and an increase in NREM after VNS administration (90), others show an increased number of periods in the REM phase (91, 92) in epilepsy patients. The sleep progressing, parasympathetic vagal tone increases and sympathetic tone decreases (93). Thus, NREM sleep have been associated with parasympathetic functioning. The ANS response is more complex regarding the REM sleep. While the REM is composed of two phases, the parasympathetic vagal tone is linked to the tonic phase and the sympathetic tone to the phasic phase (94).

Altogether, these results are in line with the benefits of multiple stimulation sessions to induce better physiological and cognitive functioning.

4.2. Side effets of taVNS

The side-effects of taVNS in clinical population is small but few is known in healthy population. Sensations reported in this study ranged from warmth, buzzing, vibration and tingling to small needles. In terms of side effects, two subjects reported numbness in their hands immediately after stimulation, while one experienced tinnitus and a rush of blood to the temples within minutes. These effects were minor and insignificant for the sample as a whole. The most common side effect is skin irritation at the stimulation site, but we had no cases of this in our study. Other side effects occurring in more than 1% of cases include: nasopharyngitis, headache, dizziness, nausea/vomiting, facial droop (65). Consequently, its use in restricted environmental contexts is conceivable.

Furthermore, a dose effect on stress perception appears to be induced by repeated sessions of taVNS stimulation. Our results highlight that the taVNS induce higher levels of perceived stress than the sham. This finding is notably observed after the 1st intervention compared to the sham but also before and after the 1st intervention as well as before the 2nd intervention compared to the sham after the 2nd intervention. This suggests that taVNS could induce a nocebo stress effect which could imply an electrical trigger sensitization. Further studies need to evaluate the nocebo hyperalgia (95). Nevertheless, time induce several modifications in the perception of stress according to the session. The taVNS stimulation seems to induce an increase subjective stress compared to the sham at the beginning but the sham tended to have higher levels of subjective stress after the 3rd intervention compared to after the 2nd intervention. The further time progresses, the more the curve might be reversed from the last intervention onwards. Interventional follow-up over several weeks would have been necessary to confirm or refute a decrease in stress for taVNS compared with *sham*. If these results were corroborated, it will be necessary to evaluate how the experimental context of the repeated stimulation session have a nocebo effect *per se*. Moreover, some participants may experience a sensitization of the nociceptive system, resulting in nociceptive pain (96). Nevertheless, this pain sensation may be a sensory illusion in the central nervous system. Therefore, some individuals may feel a pain hypersensitivity towards the taVNS stimulation.

4.3. Implication of PNS baseline level to the positive outcomes of taVNS stimulation

The HPd profile had a better HRV flexibility and self-similarity reveal by nonlinear indices compared to the LPd profile. Nonlinear indices have the potential to express added behavioral components that traditional temporal and frequential domains cannot capture and were associated with better health outcomes (39, 97).

Although the literature is cautious about the interpretation of non-linear indices, our results highlight that high parasympathetic activation reflects greater complexity of the cardiac signal. These parameters were mostly correlated with the RMSSD (97), the index used to create our profiles, and which provides a reflection of parasympathetic activity. One recommendation for assessing the effects of taVNS is to measure efferent VN activity by HRV. Modulation of VN is achieved with taVNS (70). Physiologically, increased efferent VN activity leads to a slowing of heart rate, via inhibition of the sinus node by the release of acetylcholine, the VN's main neurotransmitter (39, 78). However, using RMSSD to measure the effect of taVNS on cardiac vagal activity, various studies have found no differences between active and sham pacing (98–101). Nevertheless, Clancy and colleagues (102) evaluated taVNS on ANS response. They applied continuous stimulation for 15 minutes with a pulse width of 200ms and a pulse frequency of 30Hz, amplitude adjusted to sensory threshold level (10-50 mA). Authors showed that taVNS significantly increased HRV in healthy participants, indicating a shift in cardiac autonomic function towards parasympathetic predominance. Microneurographic recordings also revealed a significant decrease in the frequency and incidence of muscle sympathetic nerve activity during taVNS. Thus, ECG measurements are considered one of the most promising biomarkers (102, 103). Recently, Machetanz and colleagues (104) highlighted that RMSSD, SD1 and SDNN could be particularly suitable biomarkers for taVNS adaptation. They also showed a decrease in HRV when stimulation was localized to the cavum conchae rather than the cymba conchae. In another study, Machetanz and colleagues (105) confirmed a decrease in HRV during stimulation of the cavum conchae. They emphasize the potential of HRV to optimally define taVNS parameters and targets.

Therefore, an increase in HRV in its parasympathetic component might be an efficient candidate for studying the mechanisms of action of taVNS (106) and may also help predict the efficacy of taVNS.

Findings also reported that the HPd profile had a higher interoceptive trusting compared to the LPd profile. Thus, participants gain confidence in their bodily sensations. Preliminary results have shown that taVNS has the potential to improve interoceptive functioning (107). These authors observed an improvement in interoceptive sensitivity, while no difference in interoceptive acuity was demonstrated. The MAIA (108) assesses interoceptive sensitivity (i.e., subjective evaluation of interoceptive signals). Further studies should be carried out to explore the impact of taVNS on the integration of interoceptive information, and the relationships with the ANS response.

Furthermore, our results suggest that a higher parasympathetic activation during taVNS is associated to a better cognitive performance at the MindPulse test (40). The HPd profile had a lower reaction to difficulty index, a higher Go/NoGo speed and a tendency to increased simple reaction time dispersion compared to the LPd profile. The reaction to difficulty index was developed to measure how an individual may cope with difficulty by accelerating or decelerating (40). Depending on the taVNS stimulation or *sham*, participants use different strategies to deal with difficulty. In the context of a higher parasympathetic activation during the taVNS stimulation, participants slow down instead of going faster for the LPd. The LPd seems to be cautious. Overall, given the role of the vagus nerve in cognitive functioning, an increase in parasympathetic HRV may be a mechanistic candidate for the impact of taVNS on executive functions (106). Borges and collaborators (84) also provided arguments that taVNS may have very specific effects on cognitive processes. Also, they showed an increase in HF during each of the cognitive flexibility tasks, although HF did not differ between the taVNS and sham condition. More recently, a study by McIntire and colleagues (109) evaluated the efficacy of transcutaneous cervical vagal nerve stimulation in attenuating the negative effects of fatigue on cognition and mood. They showed that the intervention group that received stimulation had significantly better results in terms of arousal and cognitive functioning after a prolonged 24-hour wakefulness. They had significantly lower rates of fatigue than the control group throughout the study (109).

Concerning sleep quality, the HPd profile had a higher total awake time during recording and tended to have a higher respiration rate during the first stage of sleep than the LPd profile. These counter-intuitive results need to be confirmed by further studies.

4.4. Countermeasure for challenging missions and professions as astronauts

taVNS is an effortless tool to implement, with fewer side-effects. Data from space analogues have highlighted the sometimes deleterious, sometimes salutogenic effects of these environments on adaptation (1, 61) and increased operational risks, as long-term stress tends to degrade human performance (110). Among astronauts, sleep deprivation is associated with abrupt changes in wake and sleep schedules, the absence of a 24-hour light-dark cycle, high workload, and physical stress. The literature has shown that poor quality sleep is one of the main factors influencing neuropsychological changes (111). Indeed, sleep disorders are frequently reported (i.e., increased sleep latency, decreased sleep efficiency, reduced delta sleep duration) (112–115). In recent years, the number of publications proposing effective countermeasures has grown steadily (54, 61, 116–119).

Given the promising results of this study on stress regulation, sleep, and executive functions in healthy adult, taVNS might be a relevant countermeasure to the pathogenic effects of missions. Therefore, there is a need for further studies to better understand the benefits of taVNS in this population, its modalities of use and the psychophysiological profile of subjects for whom taVNS is most effective. If positive effects on cognitive, psychological, physiological are confirmed in healthy population, taVNS could be considered as a countermeasure for several challenging population including military, emergency as in crisis situation.

5. Limitations

This study has several methodological shortcomings. The first is the small sample size, and an imbalance between male and female, and right- and left-handed subjects. Secondly, our results are dependent on the conditions in which our participants found themselves at each passage. The lack of control of life events between each of the sessions can constitute a bias. Thirdly, psychological and interoceptive data (i.e., collected through questionnaires) are subjective measures. Intelligent sensors would provide more objective measures of subjects' adaptation. Fourthly, no longitudinal monitoring was carried out outside the intervention period. Regular monitoring beyond the study period would have enabled us to assess the evolution of the observed effects.

6. Conclusion

The present study found main findings: (1) benefits of three sessions per weeks of taVNS instead of a single session; (2) positive outcomes of taVNS to improve physiological and psychological functioning as well as sleep quality; (3) taVNS intervention is not suitable for everyone ; (4) the level of the increase in parasympathetic functioning could be an indicator of the positive effects of the taVNS stimulation. Overall, these results offer promising health outcomes for extreme missions and occupations, as astronauts in the light of future space missions. This may be a relevant countermeasure to deal with intense stressors. Further studies are needed to confirm our results.

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8. Supplementary Material

Cognition. The reaction to difficulty index at intervention (p = .768, BF_{10} = .232), session (p = .592, BF_{10} = .254), session*intervention (p = .731, BF_{10} = .056) did not change. The simple reaction time at intervention (p = .678, BF_{10} = .241), session (p = .834, BF_{10} = .227), session*intervention (p = .265, BF_{10} = .055); outliers' answers at intervention (p = .645, BF_{10} = .245), session*intervention (p = .632, BF_{10} = .230); simple reaction time dispersion at intervention (p = .541, BF_{10} = .248), session*intervention (p = .938, BF_{10} = .266) for the alertness function did not change.

Similar results were found for the executive speed at intervention (p = .792, BF_{10} = .230), session (p = .835, BF_{10} = .227), session*intervention (p = .218, BF_{10} = .051); choice errors on precision at intervention (p = .453, BF_{10} = .286), session (p = .777, BF_{10} = .281), session*intervention (p = .115, BF_{10} = .065); reaction time dispersion with categorization at intervention (p = .173, BF_{10} = .517), session (p = .824, BF_{10} = .228), session*intervention (p = .522, BF_{10} = .112) for the orientation/ selective attention function.

Moreover, speed categorization at intervention (p = .283, BF_{10} = .375), session (p = .842, BF_{10} = .227), session*intervention (p = .475, BF_{10} = .083); cognitive load at intervention (p = .803, BF_{10} = .229), session (p = .969, BF_{10} = .223), session*intervention (p = .311, BF_{10} = .051); Go/NoGo speed at intervention (p = .951, BF_{10} = .223), session (p = .966,

BF_{10} = .223), session*intervention (p = .577, BF_{10} = .049) for the executive control function did not change.

The total numbers of errors at intervention (p = .838, BF_{10} = .227), session (p = .838, BF_{10} = .227), session*intervention (p = .494, BF_{10} = .049); anticipatory errors at intervention (p = .733, BF_{10} = .235), session (p = .792, BF_{10} = .230), session*intervention (p = .902, BF_{10} = .053); erroneous errors at intervention (p = .353, BF_{10} = .326), session (p = .647, BF_{10} = .244), session*intervention (p = .155, BF_{10} = .079); inhibition errors at intervention (p = .353, BF_{10} = .326), session (p = .647, BF_{10} = .244), session*intervention (p = .155, BF_{10} = .122); cognitive load errors at intervention (p = .715, BF_{10} = .237), session (p = .878, BF_{10} = .225), session*intervention (p = .368, BF_{10} = .050); conjoint errors at intervention (p = .473, BF_{10} = .279), session (p = .473, BF_{10} = .279), session*intervention (p = .101, BF_{10} = .068) did not change.

HRV. None of the differences in the following measures reached significance: HR at intervention (p = .131, BF_{10} = .417), session*intervention (p = .125, BF_{10} = .605); RR intervals at intervention (p = .134, BF_{10} = .583), session*intervention (p = .155, BF_{10} = .629); SDNN at intervention (p = .519, BF_{10} = .265), session (p = .117, BF_{10} = .629); RMSSD at intervention (p = .165, BF_{10} = .505), session (p = .639, BF_{10} = .244); pNN50 at intervention (p = .245, BF_{10} = .398), session (p = .732, BF_{10} = .234), session*intervention (p = .032, BF_{10} = .090); LF at intervention (p = .841, BF_{10} = .227), session (p = .257, BF_{10} = .391), session*intervention (p = .075, BF_{10} = .084); HF at intervention (p = .165, BF_{10} = .505), session (p = .639, BF_{10} = .244); LF/HF ratio at intervention (p = .814, BF_{10} = .229), session (p = .735, BF_{10} = .235), session*intervention (p = .256, BF_{10} = .051); SD1 at intervention (p = .165, BF_{10} = .505), session (p = .639, BF_{10} = .244); SD2 at intervention (p = .606, BF_{10} = .249), session (p = .104, BF_{10} = .687); SD ratio at intervention (p = .523, BF_{10} = .268), session (p = .943, BF_{10} = .223), session*intervention (p = .693, BF_{10} = .061); α1 at intervention (p = .588, BF_{10} = .254), session (p = .884, BF_{10} = .225), session*intervention (p = .388, BF_{10} = .057); α2 at intervention (p = .469, BF_{10} = .282), session (p = .982, BF_{10} = .009), session*intervention (p = .189, BF_{10} = .141); SampEn at intervention (p = .288, BF_{10} = .372), session (p = .925, BF_{10} = .224), session*intervention (p = .708, BF_{10} = .079).

Monitoring sleep. Among the unique session, no significant differences were detected for total time recording at time (p = . 256, BF_{10} = .506), intervention (p = .199, BF_{10} = .591), time*intervention (p = . 533, BF_{10} = . 306); total sleep time at time (p = .275, BF_{10} = .483), intervention (p = .142, BF_{10} = .733), time*intervention (p = .548, BF_{10} = .359); sleep onset latency at time (p = .103, BF_{10} = .885), intervention (p = .190, BF_{10} = .590), time*intervention (p = .404, BF_{10} = .542); wake after sleep at time (p = .195, BF_{10} = .615), intervention (p = .845, BF_{10} = .298), time*intervention (p = .955, BF_{10} = .177); total awake time during recording at time (p = .809, BF_{10} = .305), intervention (p = .502, BF_{10} = .361), time*intervention (p = .861, BF_{10} = .105); minutes of N1 sleep stage at time (p = .786, BF_{10} = .307), intervention (p = .679, BF_{10} = .320), time*intervention (p = .966, BF_{10} = .095); minutes of N2 sleep stage at time (p = .428, BF_{10} = .388), intervention (p = .318, BF_{10} = .455), time*intervention (p = .964, BF_{10} = .176); minutes of N3 sleep stage at time (p = .618, BF_{10} = .328), intervention (p = .097, BF_{10} = .956), time*intervention (p = .351, BF_{10} = .131); minutes of non-rapid eyes movement sleep stage at time (p = .665, BF_{10} = .321), intervention (p = .099, BF_{10} = .967), time*intervention (p = .638, BF_{10} = .297); minutes of rapid eyes movement sleep stage at intervention (p = .440, BF_{10} = .288), time*intervention (p = .513, BF_{10} = .365); percentage of N1 sleep stage at time (p = .525, BF_{10} = .353), intervention (p = .310, BF_{10} = .462), time*intervention (p = .898, BF_{10} = .161); percentage of N2 sleep stage at time (p = .511, BF_{10} = .356), intervention (p = .544, BF_{10} = .346), time*intervention (p = .269, BF_{10} = .118); percentage of N3 sleep stage at time (p = .349, BF_{10} = .433), intervention (p = .515, BF_{10} = .356), time*intervention (p = .800, BF_{10} = .149); percentage of non-rapid eyes movement sleep stage at intervention (p = .440, BF_{10} = .174), time*intervention (p = .871, BF_{10} = .027); percentage of rapid eyes movement sleep stage at time (p = .137, BF_{10} = 1.000), intervention (p = .914, BF_{10} = .288), time*intervention (p = .519, BF_{10} = .386); sleep efficiency at time (p = .594, BF_{10} = .334), intervention (p = .115, BF_{10} = .873), time*intervention (p = .875, BF_{10} = .298); sleep onset in seconds at time (p = .525, BF_{10} = .352), intervention (p = .593, BF_{10} = .335), time*intervention (p = .249, BF_{10} = .112); latency to persistent sleep at time (p = .183, BF_{10} = .595), intervention (p = .108, BF_{10} = .836), time*intervention (p = .183, BF_{10} = .518); mean respiration rate during the night at time (p = .813, BF_{10} = .305), intervention (p = .772, BF_{10} = .308), time*intervention (p = .640, BF_{10} = .096); mean respiration rate during total awake time during recording epochs at time (p = .711, BF_{10}

= .315), intervention (p = .681, BF_{10} = .319), time*intervention (p = .431, BF_{10} = .099); mean respiration rate during N1 epochs at time (p = .542, BF_{10} = .348), intervention (p = .637, BF_{10} = .327), time*intervention (p = .525, BF_{10} = .114); mean respiration rate during N2 epochs at time (p = .760, BF_{10} = .310), intervention (p = .879, BF_{10} = .300), time*intervention (p = .662, BF_{10} = .091); mean respiration rate during N3 epochs at time (p = .950, BF_{10} = .298), intervention (p = .790, BF_{10} = .307), time*intervention (p = .487, BF_{10} = .087); mean respiration rate during rapid eyes movement epochs at time (p = .809, BF_{10} = .305), intervention (p = .911, BF_{10} = .343), time*intervention (p = .566, BF_{10} = .103).

Among the repeated session, no significant differences were detected for total recording time at time (p = . 172, BF_{10} = .282), intervention (p = .102, BF_{10} = .382); total sleep time at time (p = .142, BF_{10} = .351), intervention (p = .157, BF_{10} = .332); sleep onset latency at time (p = .785, BF_{10} = .314), intervention (p = .493, BF_{10} = .366), time*intervention (p = .048, BF_{10} = .118); wake after sleep onset at time (p = .579, BF_{10} = .351), intervention (p = .102, BF_{10} = .903); total awake time during recording at time (p = .816, BF_{10} = .310), intervention (p = .948, BF_{10} = .303), time*intervention (p = .701, BF_{10} = .097); minutes of N1 sleep stage at time (p = .480, BF_{10} = .362), intervention (p = .932, BF_{10} = .303), time*intervention (p = .010, BF_{10} = .112); minutes of N2 sleep stage at time (p = .444, BF_{10} = .391), intervention (p = .365, BF_{10} = .429), time*intervention (p = .085, BF_{10} = .157); minutes of N3 sleep stage at time (p = .328, BF_{10} = .405), intervention (p = .081, BF_{10} = 1.000), time*intervention (p = .416, BF_{10} = .457); minutes of non-rapid eyes movement sleep stage at time (p = .188, BF_{10} = .622), intervention (p = .098, BF_{10} = .927); minutes of rapid eyes movement sleep stage at time (p = .524, BF_{10} = .356), intervention (p = .984, BF_{10} = .303), time*intervention (p = .085, BF_{10} = .104); percentage of N1 sleep stage at time (p = .749, BF_{10} = .311), intervention (p = .234, BF_{10} = .537), time*intervention (p = .211, BF_{10} = .170); percentage of N2 sleep stage at time (p = .916, BF_{10} = .304), intervention (p = .984, BF_{10} = .303), time*intervention (p = .525, BF_{10} = .094); percentage of N3 sleep stage at time (p = .362, BF_{10} = .444), intervention (p = .218, BF_{10} = .595), time*intervention (p = .366, BF_{10} = .250); percentage of non-rapid eyes movement sleep stage at time (p = .461, BF_{10} = .391), intervention (p = .404, BF_{10} = .418), time*intervention (p = .995, BF_{10} = .164); percentage of rapid eyes movement sleep stage at time (p = .607, BF_{10} = 345), intervention (p = .405, BF_{10} = .415), time*intervention (p = .994, BF_{10} = .136); sleep efficiency at time (p = .468, BF_{10} = .384), intervention (p = .445, BF_{10} = .393), time*intervention (p = .201, BF_{10} = .149); sleep onset in seconds at time (p = .554, BF_{10} = .354), intervention (p = .710, BF_{10} = .324), time*intervention (p = .329, BF_{10} = .112); latency to persistent sleep at time (p = .716, BF_{10} = .322), intervention (p = .315, BF_{10} = .445); mean respiration rate during the night at time (p = .583, BF_{10} = .345), intervention (p = .979, BF_{10} = .303), time*intervention (p = .910, BF_{10} = .101); mean respiration rate during total awake time during recording epochs at time (p = .708, BF_{10} = .322), intervention (p = .989, BF_{10} = .303), time*intervention (p = .687, BF_{10} = .120); mean respiration rate during N1 epochs at time (p = .729, BF_{10} = .319), intervention (p = .950, BF_{10} = .304), time*intervention (p = .962, BF_{10} = .098); mean respiration rate during N2 epochs at time (p = .518, BF_{10} = .365), intervention (p = .824, BF_{10} = .311), time*intervention (p = .955, BF_{10} = .110); mean respiration rate during N3 epochs at time (p = .695, BF_{10} = .324), intervention (p = .543, BF_{10} = .353), time*intervention (p = .246, BF_{10} = .113); mean respiration rate during rapid eyes movement epochs at time (p = .292, BF_{10} = .342), intervention (p = .905, BF_{10} = .304), time*intervention (p = .953, BF_{10} = .105).

Synthèse des résultats principaux

L'étude SATE avait pour objectifs principaux : (1) investiguer l'impact de la taVNS sur le fonctionnement cognitif, psychologique, physiologique incluant l'ANS ainsi que (2) étudier les bénéfices du nombre de session de taVNS.

Si la stimulation taVNS a reçu ces dernières années un intérêt croissant pour ses nombreux bienfaits sur la santé, nos résultats chez des sujets neurotypiques ne sont pas aussi positifs. Les hypothèses ne sont globalement pas validées même si une carte d'effets bénéfiques est observée. Nos résultats mettent en évidence un avantage de la modalité d'utilisation en session répétée (i.e., à raison de trois par semaines) par rapport à une session unique. De plus, la stimulation répétée sur une semaine par la taVNS permettrait d'améliorer le fonctionnement physiologique et psychologique ainsi que la qualité du sommeil. Néanmoins, la taVNS ne semble pas convenir à tous les individus, notamment l'hypothèse de différence inter-individuelle de seuils de sensibilité à la douleur doit être posée. Enfin, l'augmentation du RMSSD durant la stimulation pourrait constituer un indicateur de l'efficacité de la stimulation. Ces résultats sont à valider sur une cohorte plus importante en tenant compte des limitations de l'étude conduite. Il conviendrait notamment d'inclure un suivi longitudinal sur plusieurs semaines des sujets ayant bénéficié d'une ou de trois stimulations par taVNS. Pour autant, ces résultats restent prometteurs et la taVNS demeure une contre-mesure d'intérêt pour le suivi de la santé des astronautes lors des prochaines missions.

Synthèse du chapitre III

L'objectif de ce troisième chapitre était de caractériser des profils d'adaptation et de proposer des contre-mesures aux plus à risque au moyen des dernières avancées médicales et technologiques avec l'objectif de maintenir des conditions opérationnelles optimales et d'assurer la santé des membres de l'équipages. Le travail amorcé au cours de ce chapitre a permis d'explorer plusieurs concepts sur le plan théorique et applicatif de l'adaptation.

Nous avons souligné sur le plan théorique des interactions entre l'état de présence et les voies intéro- et extéroceptives, et l'intérêt d'une approche par *machine learning* pour identifier des profils d'adaptation avant le départ en mission. Nos résultats mettent en évidence que la réponse de l'ANS et l'intégration des informations intéroceptives constituent des facteurs transdiagnostiques qui peuvent alerter sur une diminution des capacités adaptatives au cours de mission. Ces deux travaux pris ensemble révèlent l'importance de mener des recherches de plus grande envergure avec une approche pluridisciplinaire pour tendre vers une compréhension plus affinée des mécanismes adaptatifs. En effet, et tel que souligné au sein de la revue de littérature de Le Roy et al. (2023a), il est fondamental d'utiliser une méthodologie intégrative pour saisir le fonctionnement d'un système. En étudiant séparément les variables qui sont impliquées dans le processus dynamique d'adaptation, il est complexe de véritablement saisir comment un organisme peut évoluer dans un environnement sous contrainte composé de multiples stresseurs. C'est au contraire en étudiant les interactions de l'organisme dans son ensemble que nous pourrons acquérir une approche holistique des mécanismes impliqués.

Les deux études théoriques ont conduit à cibler trois approches de contre-mesures présentant un intérêt pour les LDSE : (1) une approche basée sur les données de la littérature interrogeant le fonctionnement *mindfulness* et la santé au regard des effets positifs de ce fonctionnement en termes d'adaptation au stress et en termes de réponses biologiques, physiologiques et psychologiques ; (2) une approche fondée sur l'activité physique immersive qui a montré, par l'enrichissement sensoriel visé, des bénéfices dans de nombreuses pathologies, notamment sur les émotions négatives ; et (3) une approche fondée sur la taVNS pour une amélioration du tonus parasympathique, qui semble pertinente en termes de maintien de la santé.

Dans leur ensemble, nos résultats confirment l'implication des voies intéroceptives et parasympathiques dans la réponse adaptative. Ils soulignent que *l'embodied virtual medicine* et la stimulation vagale constituent deux approches pertinentes qui pourraient contribuer à un renforcement de l'interaction corps-cerveau. Certes, ces études restent préliminaires mais nos résultats sont prometteurs pour avancer vers des solutions soutenant un meilleur maintien des capacités adaptatives et une prise en charge personnalisée en milieu sous contrainte.

Au terme de ce travail expérimental, nous avons pu étudier l'impact des environnements analogues à l'espace sur les capacités adaptatives physiologiques, psychologiques, cognitives et sensorielles, explorer le lien entre les variables intéro- et extéroceptives ainsi qu'émotionnelles, établir des profils d'adaptation au moyen de l'intelligence artificielle et investiguer trois approches de contre-mesures. L'ensemble des travaux qui découlent de ces résultats seront discutés au sein de la discussion générale qui suit.

DISCUSSION

Quand tu auras goûté au vol,
tu marcheras toujours sur la terre
les yeux tournés vers le ciel,
car c'est là que tu as été, et c'est là
que tu voudras toujours retourner

Leonard de Vinci

Le ciel et les étoiles ont toujours fasciné l'espèce humaine, et nombreux ont été les visionnaires qui, au fil des âges, nous ont rapprochés un peu plus de la découverte de notre Univers. Au IVème siècle, le philosophe Aristote, ancien disciple de Platon, démontrait que la Terre est sphérique dans son Traité du ciel. Il y distinguait le monde « sublunaire » situé entre la Terre et la Lune, et le monde « supralunaire » situé au-delà. En 1609, le mathématicien, géomètre et physicien Galilée s'inspira d'une longue-vue pour créer une des premières lunettes astronomiques. Cet instrument permit à l'œil humain d'observer pour la première fois plus distinctement la Lune, la Voie lactée, les planètes, leurs satellites et de découvrir une partie de ce qui compose notre Univers. Durant de longs siècles, il fut impossible de quitter l'observation pour une exploration physique de l'espace. Seuls les progrès technologiques du XX^{ème} siècle ont rendu imaginable le voyage vers l'espace inconnu. C'est sous l'effet de la Seconde Guerre Mondiale que le progrès s'est soudainement accéléré. Nous sommes aujourd'hui face à un nouvel engouement pour le spatial et son exploration avec des enjeux d'allongement des durées et des distances des missions spatiales ; il ne s'agit plus seulement d'aller vers une plus orbite basse terrestre (*low earth orbit* en anglais) mais bien au-delà, vers l'orbite haute terrestre (*high earth orbit* en anglais).

Discussion générale

Ce travail de Thèse avait deux objectifs principaux :

1. Évaluer l'impact des environnements analogues à l'espace en environnements isolés et confinés (*isolated and cofined environment*, ICE) ; extrêmes et inhabituels (*extreme and unusual environment*, EUE) sur des professionnels et sur des sujets sains afin de mieux appréhender l'adaptation psychologique, cognitive, physiologique, sensorielle et comportementale aux contraintes environnementales.
2. Caractériser des profils d'adaptation et proposer des contre-mesures aux plus à risque en s'appuyant sur des avancées médicales et technologiques récentes afin de maintenir des conditions opérationnelles optimales et d'assurer la santé des membres de l'équipage.

Au cours de l'ensemble des recherches menées (Figure 3), nous avons pu mettre en évidence un certain nombre de constats qui apportent des éléments de connaissances d'intérêt en vue des prochains vols spatiaux de longue durée (*long duration space flight*, LDSE) que nous nous proposons de discuter. Ces constats découlent en premier lieu de la synthèse de la littérature sur l'impact de l'espace et ses milieux analogues sur l'aspect temporel, psychiatrique, psychologique, cognitif, physiologique, neurophysiologique, sensoriel et de récupération (recherche PRISMA) qui a été présentée dans le chapitre I. Ce travail de synthèse conduit à proposer des recommandations pour les expérimentations scientifiques futures au sein des milieux analogues. Viennent ensuite les résultats des études présentées dans le chapitre II. Ils apportent des lignes directrices au regard des réponses psychophysiologiques, sensorielles et cognitives étudiées au cours de l'adaptation dans ces milieux analogues à l'espace (recherches ENACT, ANTIDOTE, RAD'LÔ, SSBN, ISHOW). Ils nous ont permis dans le chapitre III d'apporter des éléments de validation d'un cadre mécanistique de l'adaptation aux analogues à l'espace. Ce cadre implique les relations entre certaines variables intéro- et extéroceptives mais également émotionnelles (recherche NEURAL NETWORKS). Ce dernier a permis de proposer une caractérisation de profils d'adaptation au moyen du *machine learning* (recherche AI). La caractérisation de ces profils d'adaptation a orienté l'évaluation de trois contre-mesures ciblant un renforcement des voies intéroceptives et de l'état de présence. Une première contre-mesure s'intéresse aux programmes de *mindfulness* et à leur intérêt pour les missions spatiales (recherche PRESENCE). Une seconde contre-mesure cible la pertinence d'une activité physique immersive qui permet de coupler les bienfaits d'un pratique physique à la technologie de réalité virtuelle (*virtual reality*, VR) (recherche APTICE). Enfin la dernière contre-mesure étudiée s'appuie sur un renforcement du tonus parasympathique vagal par une stimulation transcutanée auriculaire du nerf vague (*transcutaneous auricular vagus nerve stimulation*, taVNS) répétée (recherche SATE).

Nous allons reprendre les résultats principaux de l'ensemble de ces études dans les points suivants de la discussion.

Les analogues des laboratoires naturels riches d'enseignements

Les environnements analogues à l'espace sont des environnements qui supportent ou simulent les missions spatiales. Ils partagent à la fois des caractéristiques communes avec l'espace et à la fois un processus de sélection rigoureux des personnels qui vont les habiter. La liste de ces analogues est longue :

- Les modules de simulation : e.g., opérations de mission en environnement extrême de la NASA (*NASA extreme environment mission operations*, NEEMO) ; analogue de l'espace pour la recherche humaine (*human exploration space analog*, HERA) ; simulation et analogue de l'exploration spatiale à Hawaii (*Hawaii space exploration analog and simulation*, HI-SEAS) ; recherche scientifique international dans une station terrestre unique (*scientific international research in a unique terrestrial station*, SIRIUS).
- Les stations en situation écologique : e.g., stations en Arctique et en Antarctique, sous-marins nucléaires lanceurs d'engins (*sub-surface ballistic nuclear-powered missile submarines*, SSBN).
- Les milieux qui recréent des conditions de microgravité : e.g., vols paraboliques, immersion sèche, alitement prolongé à tête déclive.

Tel que mis en évidence dans la recherche PRISMA, ces analogues sont fondamentaux car ils présentent l'avantage de permettre aux chercheurs de collecter des données en environnement écologique, c'est-à-dire en condition environnementale naturelle réelle. Ils permettent ainsi d'évaluer, en profondeur et avec un certain contrôle des biais, les modifications des réponses psychophysiologiques, cognitives et sensorielles sur la santé. Leur importance est d'autant plus grande que les expérimentations menées dans l'espace ne concernent qu'un nombre limité d'astronautes, rendant difficile les modélisations. Les environnements analogues constituent ainsi une véritable opportunité pour mener des recherches complexes qu'exigent les vols spatiaux. Au sein de nos recherches étudiant l'impact de ces milieux exceptionnels sur les réponses psychologiques, physiologiques, cognitives et sensorielles, nous avons pu nous confronter à cinq analogues spatiaux : les vols paraboliques en microgravité (ENACT), la simulation en tenue de scaphandre au risque nucléaire, radiologique, biologique, et chimique (*chemical, biological, radiological and nuclear*, CBRN) (ANTIDOTE), la simulation de survie en mer (RAD'LÔ), le SSBN (SSBN), et la station de recherche en Antarctique Dumont d'Urville (*Dumont d'Urville station*, DDU ; ISHOW).

Le Tableau 2 reprend les caractéristiques environnementales et les stresseurs auxquels les individus, professionnels ou non, ont été confrontés.

Tableau 2

Caractéristiques environnementales & stresseurs présents au sein des analogues

	ENACT	ANTIDOTE	RAD'LÔ	SSBN	ISHOW
Caractéristiques environnementales					
Milieu	Avion	Jardins	Radeau gonflable & dur	Sous-marin nucléaire	DDU
Températures (°C)	17°C à 20°C	8°C à 14°C	16°C à 17°C	15°C à 20°C	-31.1°C à 5.2°C
Pression barométrique (hPa)	825	1010	1014	CD	980
Niveau de gravité (g)	0 à 1.3	1	1	1	1
Sortie urgente	Sous-conditions	NA	Impossible	Sous-conditions	Sous-conditions
Danger	+	NA	+++	+++	+
Système support de vie	NA	++	++	+++	+++
Intimité	NA	NA	- - -	- - -	- -
Confinement	+	NA	+++	+++	++
Isolement	NA	NA	+++	+++	+++
Extreme	+	+	+++	+++	++
Inhabituel	+	+	+++	+++	+++
Inconfort physique	NA	++	+++	++	++
Habits de protection	NA	++	+	NA	+
Photopériodicité	NA	NA	NA	+++	+++
Rythmes circadiens	NA	NA	- -	- - -	- -
Privation sensorielle	+	+++	+++	+++	+++
Bruit	+	NA	+	++	++
Radiation (mSv)	NM	NM	NM	CD	NM
CO_2 (ppm)	NM	NM	NM	CD	NM

Équipement	NA	NA	- - -	- -	-
Stresseurs					
Équipage	Mixte	Mixte	Mixte	Masculin	Mixte
Taille	17	27	21	19	17
Age	41.35 ± 8.95	31.90 ± 7.0	22 ± 6.3	29.73 ± 6.94	31.73 ± 10.56
Genre (femme/homme)	23.52%/76.47%	22.22%/77.77%	33.33%/66.66%	100%	11.76%/88.23%
Différences culturelles	NA	NA	NA	NA	NA
Durée (jours)	1	1	7	80	365
Temps libre	- -	- -	+++	+	+++
Charge de travail	-	++	- - -	++	-
Rotations d'équipes	NA	NA	NA	++	++
Communication	++	+++	+++	+++	++
Tâches	Expérimentations scientifiques	Gestion des blessés, respect de la chaine de décontamination	Survivre, gestion des consommables	Spécifications liées à la mission, gestion des consommables, entretien des équipements	Spécifications liées à la mission, gestion des consommables, entretien des équipements

Note. ENACT = vols paraboliques en microgravité ; ANTIDOTE = simulation au risque nucléaire, radiologique, biologique, et chimique avec port de scaphandre ; RAD'LÔ = simulation de survie en mer ; SSBN = patrouille à bord d'un sous-marin nucléaire lanceur d'engins ; ISHOW = hivernage en Antarctique ; DDU = station Dumont d'Urville ; CD = classé défense ; NA = non applicable, c'est-à-dire inexistant ou aucune limite particulière ; NM = non mesuré.

Ce tableau récapitulatif des contraintes des environnements étudiés dans le cadre de ce travail souligne une homogénéité des températures (excepté pour la recherche ANTIDOTE qui a eu lieu en extérieur et la recherche ISHOW qui a eu lieu en Antarctique), du niveau de gravité (excepté pour la recherche ENACT qui a impliqué des périodes d'hypergravité et de microgravité), et de la composition des équipages (excepté pour la recherche SSBN composée exclusivement de marins de sexe masculin) (Tableau 2). Le dernier point met en évidence une sous-représentation du genre féminin au sein des milieux analogues. Par ailleurs, en milieu de SSBN et à DDU, là où les durées de missions sont les plus longues, la représentation des femmes est nulle voire presque inexistante. Ainsi, des recherches restent encore à mener pour améliorer la connaissance sur l'impact du genre dans l'adaptation aux contraintes des environnements analogues en s'attachant à une meilleure répartition homme/femme au sein des équipages. Ce constat est d'autant plus important que la question de la mixité se pose comme un élément d'équilibre pour le voyage vers Mars (Bell et al., 2015 ; Holland & Curtis, 1998 ; Manzey, 2004 ; Zorzano, 2020). Également, une homogénéité culturelle existe entre nos environnements pointant en miroir la non-prise en compte du facteur culturel dans nos résultats. Pour autant, cet aspect est crucial dans la composition des équipages d'astronautes.

Au regard de ces ressemblances, les analogues étudiés diffèrent sur de nombreux points. La disparité la plus importante au sein de nos environnements reste la durée de mission allant d'un à 365 jours. Trois de nos environnements (RAD'LÔ, SSBN, ISHOW) partagent également un manque d'intimité, un confinement, un isolement, l'extrême, l'inhabituel, une privation sensorielle, un inconfort physique importants, ainsi qu'une limitation dans les équipements à disposition. Il s'agit des analogues les plus fidèles au milieu spatial parmi ceux que nous avons étudiés. De plus, il convient de préciser qu'il s'agit de ceux pour lesquels les durées de missions étaient les plus importantes (SSBN et ISHOW) ou le nombre de stresseurs le plus intense (RAD'LÔ). Dans le détail, aucun analogue étudié ne parait être véritablement comparable, ne serait-ce que par la durée de mission (excepté pour ISHOW). Au regard de ce tableau, certaines caractéristiques n'ont pas été prises en compte (Tableau 2). C'est le cas notamment des possibilités de communication avec l'extérieur. Or, la communication est fondamentale pour mener à bien la mission et permettre le maintien de la sécurité des membres de l'équipages. De plus, certaines mesures ne sont pas enregistrées telles que le niveau de radiation et le niveau de CO_2. Cette information est mesurée à bord du SSBN mais est confidentielle. La seule chose que nous savons c'est qu'il existe un niveau supérieur de CO_2 comparativement à celui de l'air ambient (i.e., 415 ppm pour le CO_2). Il est à noter que le niveau de radiation cosmique au sol en France varie de 0.30 mSv/an à 1.1 mSv/an d'après l'Institut de radioprotection et de sureté nucléaire (INRS, 2023). Dans le cadre des vols paraboliques, cette exposition est toujours plus importante en raison de l'augmentation du niveau de radiation avec l'altitude. Dans le cadre de la recherche ENACT, le niveau de radiation cosmique devait avoisiner les 0.0054 mSv. Le reste des caractéristiques environnementales et des stresseurs à bord sont variables d'un milieu à l'autre. Ces différentes caractéristiques environnementales des analogues à l'espace pointent des divergences avec l'environnement spatial. La comparaison proposée dans le Tableau 2 souligne la nécessité de prendre en compte les différences environnementales dans les études d'impacts des missions dans les analogues et pose la question de l'extrapolation des résultats. Il n'en reste pas moins que le milieu du SSBN revêt un nombre important de similitudes avec une navette spatiale. Il est proposé comme un des analogues le plus fidèle aux missions spatiales (Le Roy et al., 2023 ; Orasanu & Lieberman, 2011 ; UK report, 2019). Un travail de réflexion nous semble encore nécessaire notamment pour déterminer quel analogue serait le plus pertinent pour étudier l'adaptation aux LDSE au regard de l'existant. Ce travail implique l'impulsion d'un *consortium* incluant à la fois les agences spatiales et les chercheurs du domaine.

Cette liste non exhaustive ne fait pas l'objet d'une reconnaissance officielle par les institutions du spatial tant les environnements analogues terrestres peuvent être multiples. Il nous parait essentiel de définir une liste précise des caractéristiques des différents environnements existants à partager avec la communauté scientifique. Une telle liste permettrait de mieux comparer les résultats des études conduites dans les analogues. Elle offrirait la possibilité d'homogénéiser la conduite d'études ciblant une même contrainte et de compiler des résultats de différentes études en connaissant mieux les risques des regroupements de données.

Une telle liste devrait notamment prendre en compte :

- Les contraintes environnementales (e.g., type de milieu, températures, pression barométrique, niveau de gravité, impossibilité de s'échapper, danger permanent, système de support de vie, intimité, confinement, isolement, inconfort physique, habits de protection, photopériodicité, rythmes circadiens, privation sensorielle, bruit, radiation, CO_2, équipement).

- Les contraintes opérationnelles (e.g., composition de l'équipage, durée de mission, temps libre, charge de travail, rotations d'équipes, communication, tâches à bord).
- Les facteurs de stress (e.g., facteurs temporels, physiologiques, psychologiques, sociaux, cognitifs, sensoriels).
- La durée et les modalités de récupération possibles.

Toutefois, il convient de souligner qu'en pratique, même si différents environnements analogues partagent des stresseurs communs, certains présentent des caractéristiques de contrainte spécifiques d'un environnement qui peuvent être pertinentes pour une question précise (Paulus et al., 2009). C'est le cas par exemple de l'environnement sous-marin au regard de l'absence de possibilité de communication des personnels avec l'extérieur. Ces spécificités constituent à la fois des limitations dans la conduite des études rendant difficile les comparaisons entre les différentes recherches et des opportunités pour étudier séparément telle ou telle contrainte d'un environnement ICE et/ou EUE. Cette richesse des possibles qu'offre l'emploi de laboratoires naturels implique de ce fait de bien caractériser ces laboratoires pour que la carte de résultats apporte la connaissance la plus complète et la moins biaisée de l'adaptation aux contraintes des missions spatiales.

Si l'objectif de disposer d'une base commune de travail pour la communauté repose sur une bonne caractérisation des contraintes, il implique aussi de conduire des réflexions afin d'harmoniser à la fois les données recueillies (i.e., socle commun de toute étude conduite dans un analogue), les temps de recueils des données, les méthodologies utilisées, les technologies (e.g., systèmes) employées et le traitement des données après la mission. Ce travail collaboratif serait en soi une avancée pour la communauté. Le corollaire d'une telle ambition est d'intégrer un regard pluridisciplinaire que nous nous sommes attachés à déployer au cours de ce travail. La pluridisciplinarité concerne l'étude d'un objet d'une seule et même discipline par plusieurs disciplines à la fois. L'interdisciplinarité a une ambition différente de celle de la pluridisciplinarité. Elle concerne le transfert des méthodes d'une discipline à l'autre. La transdisciplinarité se détache de la pluridisciplinarité et de l'interdisciplinarité par sa finalité. Elle sort en effet du cadre de la recherche disciplinaire pour chercher à répondre aux questions relatives à ce qui est à la fois entre les disciplines, à travers les différentes disciplines et au-delà de toute discipline. Sa finalité est la compréhension du monde présent pour un point précis, voire une question précise. C'est donc une vision intégrative qui est proposée dans ce travail. Finalement, si l'enjeu est bien celui de comprendre comment soutenir l'adaptation des astronautes dans les LDSE, l'approche transdisciplinaire s'impose. Edgar Morin (1997) considère la transdisciplinarité comme une nécessité pour la recherche contemporaine en raison de l'évolution des contenus de la connaissance. Selon lui, il n'est plus désormais question d'accumuler des savoirs fragmentés – le rôle de la science serait alors de les compartimenter dans des disciplines bien délimitées – mais d'utiliser les connaissances les plus diverses pour construire un savoir scientifique réactif et pratique répondant aux problématiques complexes comme l'est celle posée par les futurs LDSE. Cette idée ambitieuse reste difficile à mettre en œuvre. Les pièges d'un travail transdisciplinaire sont nombreux, particulièrement en termes méthodologiques. Plus encore que pour toute recherche, la recherche spatiale est particulièrement à risque d'un excès d'enthousiasme, excès probablement le plus répandu des études transdisciplinaires. Le chercheur risque de se laisser entraîner dans la découverte de connaissances nouvelles au-delà de son seul domaine d'expertise. Cette approche par la complexité s'avère néanmoins incontournable. Une première impulsion a été lancée lors de la mission de l'astronaute américain Scott-Kelly (Garrett-Bakelman et al., 2019). Cependant, ce travail doit poursuivre son chemin en incluant un nombre plus important de champs disciplinaires et d'échanges. Si la recherche n'a pu faire d'avancée majeure depuis les années 80, une des principales raisons réside peut-être dans cet aspect.

A l'issue de cette synthèse de la littérature, soulignant certains des enjeux importants de la recherche dans le paysage du spatial, la variabilité inter-individuelle émerge comme un objet de recherche qui demande à être mieux appréhendé. Sa non-prise en compte constitue dans certaines études un biais non négligeable dans les résultats rapportés. Si chaque astronaute est sélectionné en prenant en compte qu'il va avoir : (1) à dépasser les contraintes les plus effrayantes pour le commun des mortels ; (2) à faire corps avec l'équipage et l'analogue qu'il habite et à mobiliser des ressources hors du commun pour réaliser à la mission ; (3) voire à survivre aux aléas, les capacités d'adaptation individuelle ne semblent pour autant pas strictement identiques. Par conséquent, les contre-mesures potentielles devront être envisagées sous l'angle du sur-mesure plutôt que d'un prêt-à-porter qui pourrait convenir à l'ensemble d'un équipage.

Au cœur de l'impact des environnements de l'extrême

Au regard de ce que nous avons précédemment décrit, les LDSE apparaissent comme un défi à haut risque qui vient interroger les capacités d'adaptation des équipages sur le plan individuel et collectif, les modes de sélection des candidats au départ, ainsi que les enjeux de prévention et de conservation des ressources.

Nous avons pu déterminer un certain nombre de résultats quant à l'impact des environnements analogues sur l'adaptation à l'issue de la synthèse de la littérature présentée dans la recherche PRISMA (chapitre I) et des différentes recherches conduites dans ce travail, ENACT, ANTIDOTE, RAD'LÔ, SSBN et ISHOW (Chapitre II).

Les résultats issus de notre revue de la littérature ont montré les conclusions suivantes :

- Aucune évidence d'un impact temporel de la mission, ce dernier ayant été majoritairement démontré dans les stations polaires et lié à des facteurs environnementaux et psychologiques.
- Impact psychiatrique modéré ne nécessitant pas un soutien psychologique.
- Dégradation psychologique lié aux facteurs environnementaux et à la durée de mission, étudiée surtout sur les versants émotionnels et de la flexibilité des stratégies de coping.
- Impact neurophysiologique avec une modification des fonctions somatosensorielle, visuelle, vestibulaire et cardiovasculaire.
- Impact physiologique lié aux facteurs environnementaux et à la durée de mission. Le facteur temporel n'étant pas linéaire au cours du temps, il peut amener à des réponses aussi bien positives que négatives en fonction de multiples facteurs tels que le nombre de stresseurs présents au sein de l'environnement et la capacité à y faire face, le moment de la mission (i.e., plus celle-ci avançant, plus les ressources peuvent s'amoindrir et le stress du retour à la vie en communauté, familiale et sociétale peut survenir) et l'engagement dans la mission dans l'environnement habité (i.e., la beauté du lieu et sa fascination peuvent outre passer l'accroissement des stresseurs).
- Aucun consensus sur une altération des performances cognitives qui serait liée aux facteurs environnementaux et de mission ainsi qu'aux biais générés par la répétition de l'utilisations des tests cognitifs.

- Dégradation sensorielle pouvant être liée aux facteurs environnementaux et à la durée de mission.
- Impact sur la récupération inversement proportionnelle à l'intensité des stresseurs présents dans l'environnement avec des effets persistants sur une période plus ou moins longue mais qui reste peu étudiée.
- Présence d'une importante variabilité inter-individuelle.
- Nécessité d'exploiter différents aspects temporels, notamment les périodes *in situ* et de récupération.
- Absence d'éléments suffisants pour définir des processus neurocognitifs générateurs d'adaptation.
- Nécessité de présenter les résultats non significatifs et les effets salutogéniques des missions.

Nos résultats du chapitre II, regroupant les recherches ENACT, ANTIDOTE, RAD'LÔ, SSBN et ISHOW, ont mis en évidence les points suivants :

- Des résultats mixtes sont démontrés quant à une altération des réponses psychologiques, physiologiques, cognitives et extéroceptives.
- La durée de mission ne serait pas nécessairement corrélée à des effets pathogéniques. Au contraire, les membres de l'équipage pourraient se réaliser personnellement dans les environnements les plus exceptionnels (ENACT, ISHOW).
- Plus la mission est longue, plus la manifestation d'un phénomène du troisième quart pourrait être observé.
- Plus l'environnement présente des stresseurs intenses, plus l'impact serait important avec la mise en évidence d'une hibernation psychologique, particulièrement observée en situation extrême prolongée (RAD'LÔ).
- L'après mission constitue un temps à part qui nécessite une nouvelle adaptation de la part des équipages. Plus les contraintes ICE/EUE ont été élevées, plus la récupération serait lente voire entraînerait une poursuite de la dégradation des réponses psychologiques et sensorielles.
- Une anxiété anticipatrice génèrerait une mobilisation plus importante de ressources (ANTIDOTE).

- La nécessité de sélectionner de façon appropriée les équipages, de les entrainer de manière la plus efficace à ce qu'ils vont vivre et le besoin majeur d'une préparation spécifique au retour à la vie quotidienne pour appréhender l'après mission. Dans le cas du tourisme spatiale (ENACT), la préparation du post mission serait à prendre en compte. Dans le cas de la mission de longue durée à DDU (ISHOW), la prise en compte d'un niveau de santé psychique optimale pourrait être un marqueur prédictif d'une adaptation tout au long de la mission. Ce dernier point suggère qu'un fonctionnement psychologique neurotypique au regard du score à l'échelle du « general health questionnaire » avant le départ n'est pas suffisant pour une adaptation optimale. Les sujets normaux mais avec quelques réponses modérées aux items de plaintes psychosomatiques auraient un profil moins protecteur au regard de la plus grande diminution de leurs capacités adaptatives. Une recherche de profils basée sur des caractéristiques psychologiques positives devrait permettre de mettre en lumière « *the right stuff* » et de générer des performances optimales.
- Un fonctionnement parasympathique élevé avant le départ en mission constituerait un facteur de protection et permettrait un maintien des capacités adaptatives ainsi qu'une une meilleure récupération.

De ces différentes observations, nous pouvons retenir deux processus qui pourraient jouer un rôle clé au cours de l'adaptation au sein des milieux analogues. Le premier processus concerne l'activité parasympathique. Notre prise en compte du fonctionnement vagal a reposé sur l'utilisation des variables issues de la variabilité de la fréquence cardiaque (*heart rate variability*, HRV). Plus précisément, nos recherches se sont focalisées sur l'indice de la moyenne quadratique des différences successives entre intervalles RR adjacents (*root mean square of differences between adjacent RR intervals*, RMSSD). Sa priorisation par rapport aux autres indices de la HRV tient au fait que le RMSSD indexe l'activité du système nerveux parasympathique *(parasympathetic nervous system*, PNS) (Berntson et al., 1997 ; Laborde et al., 2017 ; Shaffer et al., 2014). Cependant, il convient de rester critique car il existe un nombre conséquent de méthodes d'analyse et d'interprétation des indices de la HRV. Il n'existe pas de consensus sur ceux à privilégier. Il reste néanmoins que les indices non linéaires devraient faire l'objet de plus amples études. Sassi et al. (2015) révèlent que ceux-ci semblent prometteurs pour expliquer des phénomènes non reflétés par les indices traditionnels temporels et fréquentiels, notamment l'état du système neuroviscéral. Ces marqueurs non linéaires apporteraient des informations sur la flexibilité et la complexité du système parasympathique qu'il serait pertinent d'intégrer dans les futures études.

Le second processus cible la réponse intéroceptive des sujets. L'approche psychologique classiquement pointe la modulation émotionnelle, la perception subjective de l'état de stress, et les stratégies de coping, voire la flexibilité du coping. Si ces derniers impliquent un mécanisme *top-down* de contrôle de l'environnement, nos résultats soulignent le rôle du système homéostasique du corps. L'information intéroceptive reflèterait la relation entre la composante vagale efférente *bottom-up* et la composante psychologique afférente ou *top-down*. L'intéroception apparait être un processus important pour appréhender l'adaptation d'un individu en ciblant l'intégration corps-cerveau. Pour autant, les méthodologies existantes pour évaluer le fonctionnement intéroceptif de la prise d'information interne à leur intégration demande à être enrichies. Des marqueurs objectifs de l'intéroception apparaissent et pourraient apporter des éléments d'intérêt pour étudier la réponse intéroceptive aux environnements ICE/EUE. Le potentiel évoqué cardiaque (i.e., synchronisation du signal électrique cardiaque et de l'activité cérébrale) serait notamment un marqueur de la qualité de l'intéroception mais non associé à la sensibilité intéroceptive (Verdonk et al., 2021).

Nos résultats inscrivent l'adaptation comme un phénomène complexe, multifactoriel, propre à chaque individu, et avec une composante dynamique importante à considérer. Sa prise en compte s'appuie sur des processus issus de plusieurs champs disciplinaires (i.e., psychologie, médecine, neurosciences, physiologie). L'adaptation est liée aux stresseurs environnementaux présents au cours de la mission, aux stresseurs inhérents la mission mais également à des facteurs propres à chacun des individus. Elle ne semble pas linéaire au cours du temps, rendant difficile toute conclusion générale sur sa trajectoire. L'évolution des stratégies utilisées par les individus dépendent véritablement de la mission, du temps et de leurs perceptions. Récemment, Nicolas et al. (2015 ; 2022) ont montré que l'adaptation était aussi liée au contrôle perçu et à la maitrise que les membres de l'équipe avaient sur l'environnement au décours des missions.

La connaissance de cette trajectoire implique par ailleurs une évaluation de l'effet cumulatif des missions dans les analogues à l'espace. Le cumul est important à considérer, notamment en termes de risque de dérive fonctionnelle allostasique. Force est de constater au regard de la littérature que le cumul est longtemps infraclinique alors même que l'individu dépasse peu à peu ses ressources adaptives. La prévention de l'état de stress chronique est d'autant plus difficile que la dérive d'adaptation qu'induit un travail sous charge allostasique est souvent insidieuse (Fava et al., 2019).

Allen et al. (2003, p. 5) ont estimé que : « *the most carefully selected and well-trained crewmembers will never be super humans* ». Ils ont précisé que le succès de la mission dépendrait de trois conditions : le vaisseau spatial, l'équipage et l'environnement. Tandis que les conditions de vie ont relativement évolué à bord, et les communications avec le monde extérieur sont devenues plus sophistiquées, il devient possible de diminuer les plaintes psychosomatiques et des troubles psychologiques et cognitifs (Le Roy et al., 2023). Néanmoins, les équipements disponibles ainsi que la qualité de vie sont tributaires de la charge utile (*payload* en anglais). De même, il n'est pas possible de modifier l'environnement. La marge de manœuvre la plus importante reposerait ainsi principalement sur les individus composants l'équipage (e.g., méthode de sélection, détection de vulnérabilité, suivi pré mission, suivi *in situ*, post mission, prise en charge personnalisée). Les exigences de la mission n'étant pas une variable interchangeable, les variables d'ajustement pourraient, outre un renforcement des voies intéroceptives et parasympathiques, se situer aussi au niveau des ressources offertes par l'environnement et par le sentiment d'efficacité personnelle. En ce sens, le modèle appelé *job demands-resources* (plus connu sous l'appellation JD-R) souligne deux processus psychologiques pour mieux appréhender l'adaptation professionnelle, fut-il extraordinaire comme l'est une mission spatiale. Le premier processus implique une sollicitation trop importante des ressources de l'individu sur le long terme qui conduit à un défaut des stratégies de compensation et à leurs épuisements *in fine*. Le second processus implique un niveau de ressources insuffisant qui conduit à l'impossibilité de répondre à la demande de l'environnement de travail. Ce modèle pourrait constituer un cadre pertinent pour étudier les ressources à cibler et à renforcer pour chacun des membres de l'équipage (Demonti & Bakker, 2007).

L'aventure se poursuit plus loin, plus haut, plus longtemps

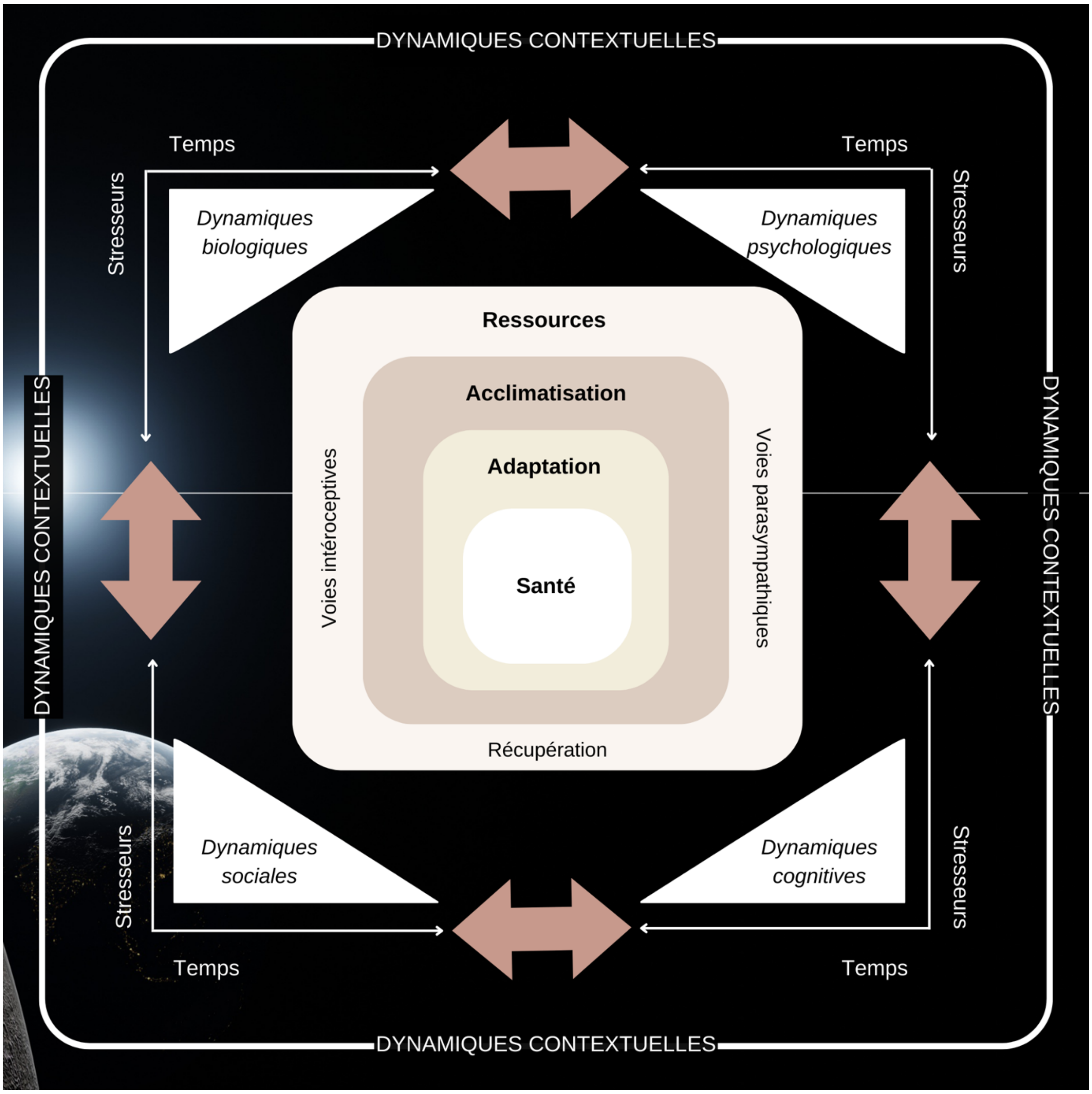
Les vols spatiaux de demain poseront des défis très différents de ceux auxquels nous avons déjà été confrontés. Ces dernières années, un nombre croissant de publications étudie des contre-mesures ciblées afin de pallier aux risques associés aux vols spatiaux et de préserver la santé des voyageurs de l'espace (Palinkas & Suedfeld, 2021 ; Salam, 2020 ; Stahn & Kühn, 2021). La recherche PRISMA a mis en évidence l'intérêt de programmes visant à enrichir les stratégies de coping, à renforcer les compétences de communication, à améliorer les ressources et leur conservation (i.e. programme de psychologie positive), à la mise en œuvre de débriefings tout au long de la mission, et ce à intervalles réguliers, à des entraînements sensorimoteurs, à des programmes d'activité physique, à une exposition à la lumière enrichie bleue et à la gravité artificielle, à l'utilisation des technologies immersives (e.g., VR, réalité augmentée, réalité mixte), ou encore à des stimulations du cerveau non invasives (voir la revue de Romanella et al., 2020, pour un état de l'art sur ces techniques).

L'objet du chapitre III était celui des contre-mesures ciblant l'adaptation. Il nous semblait important pour proposer et d'évaluer des contre-mesures d'intérêt afin d'ancrer nos réflexions sur les acteurs de l'adaptation que nos études de terrain ont souligné. Le point de départ a donc été de valider la pertinence des variables adaptatives centrées sur l'intégration corps-cerveau. Cette étape préliminaire nous a ensuite conduit à questionner ce qui pouvait améliorer ces capacités adaptatives. Un premier travail s'est donc attaché à étudier le lien entre les variables intéro- extéroceptives et émotionnelles, et à déterminer si nous pouvions identifier des profils d'adaptation fondés sur l'état psychophysiologique avant le départ en mission. Des modélisations ont été faites et ont montré le rôle de l'intégration intéroceptivo-vagale dans la genèse des difficultés d'adaptation. Ces modélisations soulignent la nature multifactorielle et complexe de l'adaptation. Au cours de la mission, il semblerait qu'aient lieu une modification du traitement des informations interoceptives, ainsi qu'une modulation des réponses vagales. Ces informations apportent des éléments d'intérêt sur les variables les plus prédictives de la réponse psychophysiologique sous contrainte. Pour autant la variabilité inter-individuelle des études prise en compte dans ces modélisations est responsable d'une variance importante qui bruite les résultats. Au terme de ce travail, les modélisations proposées soulignent la faisabilité de combiner plusieurs études pour prendre en compte les réponses individuelles au décours des missions analogues à l'espace. Elles ouvrent la voie pour un partage des données au sein la communauté scientifique qui travaille sur le sujet de l'adaptation de l'espèce humaine aux contraintes de l'espace. Cette approche permettrait de disposer d'un jeu de données conséquent qui permettrait des modélisations de meilleure qualité et donc plus informatives. Au-delà, l'intérêt des approches par l'AI se pose quant à son usage pour la sélection, le suivi de la préparation et à termes le monitoring pendant la mission.

Initialement, nous pensions pouvoir apporter une réponse concrète sur les variables en jeu au cours de l'adaptation. Cependant, face à de nombreuses limites, dont la prise en compte de la variabilité inter-individuelle et les outils utilisés, nous ne pouvons qu'apporter des pistes de réflexion. Ces réflexions s'inscrivent dans le modèle biopsychosocial décrit au sein de la recherche PRISMA (Figure 28) en le précisant par l'intégration des variables intéroceptive et vagale. Pinna et Edwards (2020) ont exploré comment le tonus vagal et l'intéroception pouvait conduire à une meilleure régulation émotionnelle en précisant leur implication dans la balance homéostasique.

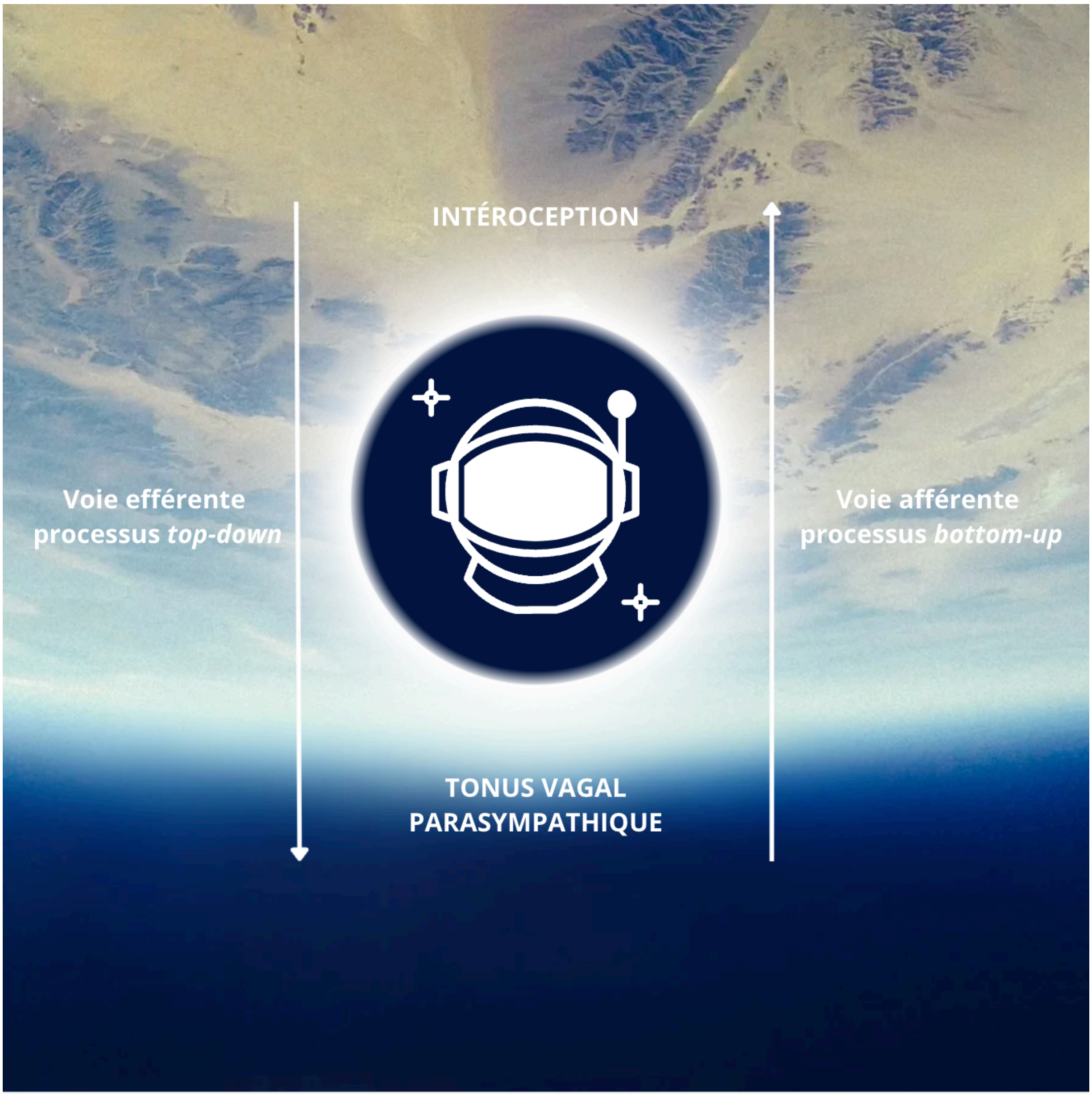
Figure 28

Mise à jour du modèle biopsychosocial au regard des résultats issus des différentes recherches



Au regard de ces cadres, nous présumons que l'intéroception pourrait être considérée comme la composante informative d'une adaptation nécessaire, la réponse de l'ANS mesurée par la HRV, en serait l'agent d'adaptation principal. Ces deux processus interdépendants ont orienté le choix des contre-mesures étudiées. Nous avons ainsi exploré des outils visant à un renforcement des voies intéroceptives et du tonus vagal en nous attachant à étudier leur pertinence pour maintenir/améliorer l'état de santé (Figure 29). Leurs résultats sont prometteurs mais méritent de plus amples investigations.

Figure 29
Processus ciblés pour les contre-mesures des LDSE



Les contre-mesures d'intérêt visent à maintenir les performances cognitives, le système moteur, à améliorer la stabilité psychologique, et/ou à augmenter la flexibilité physiologique. Au regard de cet existant, il ressort différents résultats des études ciblant les enjeux des contre-mesures présentées dans le chapitre III (i.e., PRESENCE, APTICE et SATE). Que ce soit l'approche comportementale (e.g., la pratique de l'activité physique) et/ou l'utilisation de technologies favorisant l'instant présent, ou encore la stimulation de la branche auriculaire vagale, les résultats soulignent certains bénéfices d'intérêt à de multiples niveaux (e.g., psychologique, physiologique, cognitif) sans pour autant aboutir à une validation permettant des recommandations d'usage. Un point commun à ces approches est de stimuler le traitement des informations sensorielles internes (SATE) et/ou externes (PRESENCE, APTICE). Elles agiraient comme un environnement sensoriel enrichi favorisant l'*embodiement*, et renforçant ainsi la capacité d'action et la perception de contrôle sur le monde.

Les résultats obtenus appellent au moins à deux remarques. La première concerne les enjeux de l'intéroception. Plusieurs méthodes existent afin de mesurer l'intéroception. Les mesures objectives restent actuellement limitées et ne semblent pas faire l'objet d'un consensus (Khalsa et al., 2018). Pour autant, nous avons montré que les voies intéroceptives étaient impliquées dans l'adaptation et pouvaient constituer un facteur transdiagnostique de détection des profils. Un véritable enjeu réside ainsi dans l'existant des méthodes de renforcement du traitement de l'information intéroceptive. Des méthodes pharmacologiques (e.g., bloquant adrénergique ou agoniste, benzodiazépines, relaxants musculaires, opioïdes) existent ainsi que des méthodes comportementales (e.g., thérapies, entraînement respiratoire assisté par capnométrie, exercices de pleine conscience, méditation, yoga) (Khalsa et al., 2018). Les stimulateurs intéroceptifs sont également prometteurs (Khalsa et al., 2018 ; Schoeller et al., 2022). Nous pouvons citer le Floatation-REST qui consiste à diminuer les entrées sensorielles extéroceptives dans le système nerveux (Feinstein et al., 2018) ou l'outil portable qui produit des stimuli tactiles continus sur la face antérieure de l'avant-bras gauche (Di Lernia et al., 2018). D'autres approches sont également étudiées que ce soient un feedback intéroceptif ou l'augmentation émotionnelle (e.g., stimulation des thermorécepteurs couplée à un stimulus audiovisuel saillent, stimulation vestibulaire galvanique) (Schoeller et al., 2022).

Une deuxième remarque concerne le cadre théorique des résultats obtenus sur les réponses parasympathiques et leur renforcement. Une approche intégrative consisterait à définir dans quelle mesure un individu serait capable de s'ajuster au besoin « du challenge pour évaluer si sa réponse est adaptée ». La théorie du réservoir vagal de Porges (1995) apporte un cadre d'étude pertinent. Il est reconnu qu'un tonus vagal élevé au repos est associé à un meilleur état de santé (Porges, 1995 ; Thayer & Lane, 2009), ce que nos résultats démontrent également. Pour autant, la réaction vagale apparait également comme un enjeu de santé qu'il conviendrait d'intégrer dans les futures études sur l'adaptation en environnements analogues à l'espace. Afin d'assurer une auto-régulation optimale, la théorie propose de prendre en compte un réservoir vagal dynamique, adaptant le niveau d'activation à la demande environnementale et aux besoins de l'organisme. La capacité de ce réservoir à s'activer et à récupérer traduirait une composante flexible de l'individu et ainsi la capacité à s'auto-réguler efficacement en fonction des besoins. Par conséquent, il serait pertinent de pouvoir évaluer ce réservoir et d'identifier comment il se comporte pour chaque individu. Cette approche impliquerait un monitoring du système parasympathique des sujets au décours des missions et de leur vécu en termes de challenges.

La temporalité des contre-mesures reste également importante à définir. Nous proposons que celles-ci doivent intervenir selon : (1) une quintuple temporalité, c'est-à-dire en amont du départ en mission (e.g., apprentissage et entraînement de stratégies de flexibilité cognitive, de régulation émotionnelle, de réservoir vagal), pre *in situ* (e.g., poursuivre l'entraînement, la gestion des ressources, la capacité à faire face au danger, élaboration d'un plan post mission), *in situ* (e.g., surveillance en temps réel, interventions des équipes médicales au sol en collaboration avec l'équipage, développement de la communication, sessions de débriefings, préparation au retour de mission), post *in situ* (e.g., sessions de debriefings, évaluation de l'état de santé au niveau biologique, psychologique, physiologique, cognitif et sensoriel, des ressources cognitives et du réservoir vagal), longtemps après le retour de mission (e.g., évaluation de l'état de santé au niveau biologique, psychologique, physiologique, cognitif et sensoriel, support psychologique en cas de nécessité) ; et (2) avec suivi en temps réel des membres de l'équipage. Une meilleure connaissance des effets des contremesures est nécessaire pour proposer des interventions ciblées adaptées à la temporalité des besoins du sujet. Cette connaissance implique de pouvoir suivre l'état de santé psychophysiologiques et les facteurs de stress liés à la mission. Ce monitoring s'avère ainsi nécessaire non seulement pour permettre une détection et une atténuation précoces des impacts générés mais avant tout pour définir une approche personnalisée ajustée à l'état psychophysiologique des astronautes. Il est important de mieux comprendre les évolutions qui ont lieu au sein des environnements pour mettre en place les bonnes contre-mesures ; ces deux axes pouvant être étudiés en simultanés.

Dans ce cadre, les contre-mesures doivent être considérées selon une approche dynamique qui peut être ajustée aux besoins individuels identifiés avant la mission, mais aussi en fonction de la durée et du type de la mission. Ainsi, des contre-mesures adaptées à chaque individu et donc personnalisées sont indispensables. Ce constat souligne qu'il est fondamental de déployer une approche intégrative avec des outils méthodologiques permettant un suivi ancré dans la temporalité des réponses psychophysiologiques pour optimiser le suivi de la santé et les modalités d'utilisation d'une boite à outils de contre-mesures.

Limitations

Ces travaux de Thèse présentent un certain nombre de limitations, majoritairement en raison des conditions opérationnelles dans lesquelles elles ont été menées :

Résultats non reproductibles en dehors de conditions spécifiques des études, et non généralisables

Nos expérimentations se sont placées dans des environnements analogues à l'espace, c'est-à-dire des milieux pour lesquels il existe une contrainte opérationnelle importante. Elles font appels à une population en excellente santé, sélectionnée et plus ou moins entrainée. En conséquence, les résultats ne peuvent s'appliquer en l'état ni à la population générale, ni à la population des astronautes.

Faible échantillon des cohortes d'étude pouvant impacter la puissance statistique

Les individus dans les milieux analogues à l'espace évoluent dans un environnement professionnel dans lequel le danger peut être prégnant. La participation à nos études se faisant sur la base du volontariat dans le respect des recherches interventionnelles sur la personne humaine, il est complexe de mener des études dans des milieux opérationnels sous contrainte. En conséquence, les faibles échantillons que nous avons dans la plupart des études constitue un reflet de la réalité du terrain et peuvent limiter notre puissance statistiques (e.g., homéodasticité, significativité, taille des effets). Elle nécessite un engagement important, et par conséquent, des temps dédiés pour effectuer la recherche. Dans le cadre de ces trois années de doctorat, il n'a pas été possible de dupliquer certaines études (e.g., plusieurs patrouilles sous-marines) pour augmenter les effectifs.

Représentation non paritaire entre les hommes et les femmes

Nos cohortes sont majoritairement représentées par une population masculine. Malheureusement, la réalité du terrain est une sous-représentation de la population féminine dans les milieux analogues à l'espace. Diverses raisons peuvent expliquer ce constat, à la fois sociétales, historiques et professionnelles. A cet égard, il existe également un déséquilibre entre les droitiers et les gauchers dont le nombre n'a pas toujours pu être contrôlé. Par conséquent, un biais a pu être introduit dans certaines de nos études, notamment au regard des différences posturales observées.

Données diverses en fonction des expérimentations

Le manque d'homogénéisation dans le recueil de données entre nos environnements analogues est inhérent à l'adaptation dont nous devons faire preuve. Celle-ci provient à la fois de la contrainte environnementale du milieu (e.g., températures extrêmes, synchronisation des systèmes) et de la contrainte de la mission (e.g., temps limité). De plus, les données psychologiques et intéroceptives sont issues de questionnaires. L'utilisation de capteurs intelligents couplée à ces mesures subjectives pourraient permettre de décrire de manière plus approfondie le fonctionnement sensoriel, physiologique et psychologique. Également, nous n'avons pu utiliser le même système pour enregistrer le biosignal cardiaque. Ces derniers ont enregistré l'électrocardiogramme (*electrocardiogram*, ECG) sur un intervalle de fréquence d'échantillonnage allant de 150 Hz à 2000 Hz. Ces choix, marqués par la contrainte de terrain à laquelle nous avons dû faire face, ont été le produit de recherche sur les systèmes les plus adaptés à chacune des situations. Sur la même lignée, les systèmes utilisés afin de recueillir la posturographie des individus n'ont pas été les mêmes sur chaque terrain (e.g., plateforme posturale Technoconcept pour les études ENACT, RAD'LO, SSBN et système des semelles connectées Feet Me pour ANTIDOTE). Nous avons par ailleurs utilisé les métriques les plus classiques dans la littérature, alors que de nombreuses métriques sont disponibles. Une approche computationnelle pourrait faire émerger les indicateurs les plus propices pour l'étude de la stabilité posturale et de sa pertinence en termes d'adaptation (Yamamoto et al., 2015 ; Verdonk et al., 2022). Par conséquent, mener des expérimentations dans les environnements analogues nécessite une flexibilité du chercheur qui, sorti des conditions de laboratoire, doit faire avec les contraintes du terrain en restant respectueux de la rigueur méthodologique et doit accepter les compromis dans le choix des données d'intérêt. Pour autant, les études en condition écologiques nous permettent véritablement de reproduire au mieux les contraintes d'une mission spatiale en intégrant ses différentes phases (e.g., trajet, incidents) pour caractériser l'impact de l'environnement sur les capacités adaptatives humaines, mieux le comprendre et mieux penser les contre-mesures et leurs modalités de déploiement.

Un suivi post mission à généraliser sur le long terme

La récupération post mission est actuellement peu étudiée au sein de la littérature. Nos études suivent des individus allant d'une à plusieurs semaines post mission mais se heurtent à un manque de soutien des institutions pour systématiser ce suivi. Un suivi longitudinal s'avère pour autant essentiel dans la mesure où, tel que mis en évidence dans le cadre de ces travaux de recherche, le post-mission constitue une période critique de réadaptation. Afin de permettre la mise en place de mesures efficientes dès la fin de mission pour préparer le retour, il est nécessaire de comprendre cette période critique (e.g., durée, réponses de l'organisme impactées). Il s'agit également d'une période critique dans l'étude de l'efficacité des contre-mesures.

Des facteurs environnementaux et individuels complexes à différencier

Il peut s'avérer difficile de différencier au sein de nos résultats, et de manière générale, les facteurs issus de stresseurs environnementaux et ceux engendrés par les stresseurs inhérents à la mission. Nous considérons l'ensemble des stresseurs présents dans les milieux analogues comme une unité qui influence l'adaptation des professionnels. Il peut s'agir d'un tout qui impacte plus ou moins les réponses cognitives, psychologiques, physiologiques et sensorielles. L'étude de ces réponses multidimensionnelles, peu importe l'origine du stresseur, apporte certaines réponses permettant d'avancer les réflexions sur les modalités de maintien opérationnel optimal. De plus, nos résultats sont dépendants des conditions dans lesquelles se trouvaient les sujets d'étude notamment en ligne de base. Il n'a pas été possible de contrôler le vécu de la semaine précédant la mesure de base.

Des outils technologiques à développer

Les systèmes utilisés au sein de ces études sont mixtes. Ils résultent de produits du commerce validés par la littérature et ayant fait leurs preuves et d'autres outils technologiques plus récents. En conséquence, l'assise historique confère une validité d'utilisation qui peut induire le risque d'un produit vieillissant, et les nouvelles technologies permettent d'acquérir des dispositifs de pointe qui peuvent manquer de développement et de validité opérationnelle. Outre cet aspect, il serait pertinent d'utiliser les mêmes systèmes d'un analogue à l'autre, notamment quand il s'agit d'enregistrer des

ECG. Par ailleurs, l'utilisation d'un système électroencéphalogramme concomitant à un électrocardiogramme permettrait de mieux appréhender la réponse de l'axe corps-cerveau.

Distinction de profils d'adaptation sur le biosignal cardiaque

Les types de profils identifiés par clustering présentés au sein de nos études répondent à des justifications scientifiques mais aussi méthodologiques. La HRV, à travers l'impact du fonctionnement parasympathique, a largement été relayée comme un marqueur d'adaptation au sein de la communauté scientifique. Nous avons proposé la formation de profils fondés sur la médiane du RMSSD, indicateur de la branche parasympathique de l'ANS. L'ajout de marqueurs comportementaux comme les indices non linéaires permettrait d'enrichir la caractérisation de ces profils via des algorithmes de clustering. Son couplage à la perception du stress subjectif a été proposé pour permettre de mettre en évidence des profils anxieux anticipateurs. A notre connaissance, la validité de cette proposition n'est pas clairement établie dans la littérature disponible.

Utilisation d'échelle adaptée aux analogues à l'espace

Nous n'avons utilisé que peu d'outils développés pour les environnements ICE/EUE. Forte de son développement récent en 2015. Pour autant, la batterie de tests cognitifs de Basner et collaboateurs (2015) a été utilisée dans plusieurs de nos milieux afin de mesurer les performances des individus. Des échelles ont été développées ces dernières années, notamment le ICE-Q de Nicolas et collaborateurs (2019), pour mesurer l'adaptation dans ses composantes sociales, émotionnelles, occupationnelles et physique spécifiquement au sein des analogues, ou encore la checklist santé mentale de Bower et collaborateurs (2019) pour évaluer la santé mentale. Leur utilisation aurait pu être judicieuse dans le cadre de ce travail afin d'alimenter les recueils de données basés sur ces outils nous inscrire dans une homogénéisation des outils utilisés en ICE/EUE que nous défendons. Nous avons fait le choix d'orienter les recueils sur des données d'intégration corps-cerveau qui ne sont pas prises en compte dans les outils cités.

Des analogues à l'espace divers

L'ensemble des analogues mobilisés au sein de ces travaux de Thèse (i.e., vols paraboliques, sous-marin nucléaire, base de recherche en Antarctique, simulations) mettent en évidence des caractéristiques environnementales complexes et diverses, avec une grande variabilité. A l'heure actuelle, il n'existe que peu de paradigmes dans lesquels il est juste de se placer. A cet égard, la revue systématique de Le Roy et collaborateurs (2023) a mis en évidence la nécessité de repenser les caractéristiques des analogues à l'espace. Un travail collégial s'avère indispensable pour véritable commencer à étudier l'impact des stresseurs environnementaux sur les réponses de l'organisme mais également pour permettre de comprendre les facteurs en tant que tel.

Une adaptation multifactorielle

L'adaptation est complexe à étudier par sa dimension multiple. Continuer la recherche pour en déterminer les mécanismes sous-jacents est plus que nécessaire. Elle fait appel à toutes les disciplines des sciences de la vie et humaine. Nous aurions pu pousser plus loin la pluridisciplinarité de cet aspect, voire oser une approche transdisciplinaire. Afin de pouvoir prédire son avancement au sein des équipages, il convient de pouvoir appréhender l'adaptation sous l'angle d'un problème multi-classe et non binaire. Il en résulterait une meilleure prédiction et ainsi une meilleure détection des individus à risque au cours de la mission, ce qui permettrait de mieux identifier les contre-mesures à proposer, à qui et avec quelle temporalité.

Perspectives

De nombreuses questions restent ouvertes pour les LDSE.

Ces dernières années, le Centre national des études spatiales (*French space agency*, CNES) a engagé des travaux prospectifs collectifs qui rassemblent des experts de champs pluridisciplinaires différents afin d'envisager les futurs possibles. Portés par l'observation de prospective spatiale Space'ibles, la troisième édition a souligné le rôle majeur que vont jouer les médecines préventives et curatives personnalisées en fonction de l'individu. Elle a mis en évidence les contraintes médicales qu'engendreront un voyage lointain tel que vers Mars (i.e., impossibilité de rapatriement ; entraînement intensif aux gestes médicaux ; conséquences des délais de communication pour la télémédecine ; risque des radiations ; alternance de gravité terrestre, microgravité et gravité partielle ; présence importante de poussière ; pluralité de gaz ; évolution rapide des pathogène et réduction de l'immunité due au confinement ; impact psychologique ; maintien difficile des compétences techniques médicales et des équipements médicaux ; problématique de gestion des consommables).

Il n'est pas sans rappeler qu'un travail de fond sur la caractérisation des environnements analogues s'avère nécessaire. L'élaboration d'un *consortium* collectif sera riche d'enseignement pour définir les lignes directrices de demain et homogénéiser les décisions. Ce dernier devra néanmoins prendre en compte les caractéristiques de demandes spécifiques que peuvent présenter certains environnements. Des méthodes de médecine préventive et personnalisées devront également être mises en place par les institutions. Afin d'assurer le succès des futures missions, il est fondamental de mieux suivre les membres de l'équipage à tous les niveaux biologiques, psychologiques, physiologiques, cognitifs et sensoriels et de mieux comprendre le processus d'adaptation et de mieux les sélectionner. La sélection passe par la définition d'un profil d'adaptation ayant des caractéristiques positives et non par un tri sur ceux qui ont une impossibilité à s'adapter. Il s'agit d'adopter un nouveau point de vue sur le choix des individus qui seront sélectionnés pour leur stabilité psychologique « hors norme », leur flexibilité cognitive, leurs capacités intéroceptives et parasympathiques élevées, leur tolérance à la frustration, leur capacité de communication, leur résistance aux stresseurs de tout type, leur détachement au sujet de l'environnement familial et social au profit d'un intérêt commun pour n'en citer que quelques-uns. Les missions LDSE exigeront un travail d'endurance à la fois psychologique, cognitif et physique.

Les approches abordées au sein de ce travail ouvrent la voie vers de nouvelles contre-mesures qui cibleraient les mécanismes en lien avec l'adaptation à savoir un renforcement de l'intégration des informations intéroceptives et du tonus parasympathique. Les travaux que nous avons menés permettent de montrer la pertinence de ces approches dont le potentiel semble prometteur. De plus amples études mériteraient d'être engagées dans ces champs afin de les évaluer en situation écologique au sein des analogues voire à bord d'une station spatiale. De plus, afin de lutter contre l'hétérogénéité entre les études il est primordial de définir des méthodologies communes en tenant compte du profil des missions LDSE. Recenser l'ensemble des outils pouvant être utilisés et étant adaptés à la contrainte des vols spatiaux est à effectuer pour ensuite définir une charte commune des variables à extraire. Homogénéiser les méthodologies de recherche signifie harmoniser les résultats et ainsi mieux généraliser ceux-ci aux missions spatiales.

Conclusion générale

Malgré l'effort de la communauté scientifique afin de mieux comprendre et mesurer l'impact des environnements analogues sur les capacités d'adaptation de l'espèce humaine, nous ne pouvons à ce jour déterminer quel sera le réel effet d'un voyage aussi loin de notre planète Terre. Les équipages d'astronautes seront confrontés à des situations où le transcendant coexistera avec le tragique, et où une juxtaposition de beauté et de puissance naturelle menaçante donnera lieu à une construction sociale unique. L'ensemble des recherches que nous avons menées ont pu mettre en évidence : (1) un impact aussi bien pathogénique qu'adaptatif en fonction de la durée de la mission et des stresseurs présents dans l'environnement, (2) la possibilité d'identifier des profils d'adaptation sur l'état psychophysiologique avant le départ ainsi que (3) la nécessité de cibler des contre-mesures qui renforcent les voies intéroceptives et le tonus vagal pour maintenir les performances. Certains membres de l'équipage seront à même de s'adapter à ces milieux hors du commun efficacement tout au long de la mission, voyant là le plus beau voyage de leur existence ; tandis que d'autres y verront le plus grand challenge de leur vie à devoir apprivoiser ces terrains d'exception. Quoi qu'il en coûte, il résultera de ce voyage un incroyable développement personnel qui jusqu'à la fin témoignera de la beauté dont chacun a été animé. L'espèce humaine n'a jamais été si proche des étoiles.

Alors qui est prêt au grand voyage ?

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A l’aube des prochaines missions spatiales de longue durée, explorer les étoiles n’a jamais été aussi réel. Ces missions exposeront les astronautes à des conditions de vie extrêmes auxquelles ils devront s’adapter. Des conditions similaires existent dans plusieurs environnements analogues sur Terre, et leurs études peuvent fournir une opportunité pour améliorer la compréhension des défis que pose l’adaptation de l’être humain sous contrainte. Ces milieux peuvent être marqués par un climat vigoureux, une absence de lumière naturelle, un danger extrême, des installations et des fournitures limitées, l’isolement des proches ou l’interaction obligatoire avec les membres de l’équipage. Ils sont rarement rencontrés par la plupart des êtres humains et concernent principalement certaines professions dans le cadre de missions limitées. L’objectif de cette Thèse est ainsi (1) d’étudier l’impact des environnements analogues à l’espace sur les capacités adaptatives humaines (i.e., psychologiques, cognitives, physiologiques et sensorielles) ; et (2) d’identifier des profils à risque au cours de la mission et d’évaluer des contre-mesures de santé pour maintenir la santé et les performances des astronautes.

L’impact de cinq environnements analogues à l’espace (i.e., vols paraboliques en microgravité et gravité partielle, simulation au risque nucléaire, radiologique, biologique et chimique, simulation de survie en mer, sous-marin nucléaire lanceur d’engins, base de recherche en Antarctique) a été étudié. Ces analogues ont été choisis comme modèle pour cibler différentes temporalités des missions spatiales (e.g., trajet, danger, confinement, durée) et intégrer les contraintes d’isolement, de confinement, d’inhabituel, voire d’extrême. Des profils d’adaptation ont été établis par un modèle de réseau d’interactions psychosensorielles et par un modèle de machine learning appliqué au fonctionnement intéroceptif et parasympathique avant le départ en mission. L’exploration de trois contre-mesures a été conduite à travers une revue de la littérature sur les technologies et programmes permettant d’améliorer l’intégration des informations sensorielles internes, le développement d’un outil permettant une activité physique immersive pour améliorer l’état de présence en renforçant les bénéfices de l’activité physique ainsi que la stimulation de la branche auriculaire du nerf vague afin de renforcer l’activité parasympathique du système nerveux autonome.

Les résultats mettent en évidence une carte des effets bénéfiques et négatifs qui demandent à être confirmés avant des applications aux milieux écologiques. Il ressort de ces 11 études scientifiques que l’adaptation est un processus multifactoriel, non linéaire au cours du temps et qui implique que les équipages soient suffisamment sélectionnés et entrainés. L’intelligence artificielle a le potentiel de notamment pouvoir identifier des profils d’adaptation sur l’état psychophysiologique avant le départ. Par ailleurs, nos résultats ont révélé la nécessité de cibler des contre-mesures qui renforcent les voies intéroceptives et le tonus vagal pour maintenir les performances des membres de l’équipage.

Ainsi, l’ensemble de ces travaux permettent de mettre en évidence certains enjeux posés par les missions spatiales de demain. Nos résultats donnent un aperçu de leurs impacts physiologiques, cognitifs, sensoriels et comportementaux afin de mieux comprendre comment les êtres humains sont capables d’adaptation. Ils fournissent un cadre pour l’étude de l’adaptation sous contrainte, particulièrement important à la lumière des prochaines expéditions spatiales plus longues vers des destinations plus lointaines.

Mots clés
Adaptation, Analogues spatiaux, LDSE, Contre-mesures, Stress

As dawn breaks on the next phase of long-duration space missions, exploring the stars has never seemed so possible. The next generation of astronauts will have to adapt to extreme living conditions. Similar conditions can be found in various analog environments on Earth, and their study is an opportunity to improve our understanding of human adaptation under stress. These environments are marked by intense climatic conditions, a lack of natural light, extreme danger, limited facilities and supplies, isolation from loved ones, and unavoidable interactions with other crew members. They are rarely encountered by most human beings, and are mainly the domain of certain professions who spend a limited time in them. The aim of this thesis is thus: (1) to study the impact of space analog environments on human adaptive capacities (psychological, cognitive, physiological and sensory); and (2) to identify profiles of people who are at risk of maladaptation during the mission, and to evaluate countermeasures that can help to maintain the health and performance of astronauts.

Five space analog environments (parabolic flight in partial and microgravity, a simulated nuclear, radiological, biological and chemical attack, a survival at sea exercise, life onboard a nuclear-powered ballistic missile submarine, and an Antarctic research base) were studied. These analogs were chosen as they correspond to various aspects of a space mission (the journey, danger, confinement, duration) and reflect the constraints found in space (isolation, confinement, the unusual, the extreme). Adaptation profiles were identified by modelling the network of psychosensory interactions, and a machine learning model applied to interoceptive and parasympathetic functioning prior to departure. A review of the literature on technologies and programs identified three countermeasures: a method to improve the integration of internal sensory information; the development of an immersive tool that enhances presence by reinforcing the benefits of physical activity; and stimulation of the auricular branch of the vagus nerve to enhance parasympathetic activity in the autonomic nervous system.

While the results identify both beneficial and negative effects, they must be confirmed before they can be applied to ecological environments. The reported 11 scientific studies show that adaptation is a non-linear, multi-factorial process, and that crews must be carefully selected and well-trained. Artificial intelligence may be able to identify adaptation profiles based on the individual’s psychophysiological state prior to departure. Finally, the findings identify the need to target countermeasures that strengthen interoceptive pathways and vagal tone to maintain crew members’ performance.

Overall, this work highlights some of the challenges of future space missions. The results provide an insight into their expected physiological, cognitive, sensory, and behavioral impacts, and provide an insight into how human beings adapt. They provide a framework for the study of adaptation under stress, which is particularly important in the light of future long duration space expeditions to more distant destinations.

Keywords
Adaptation, Spatial Analogs, LDSE, Countermeasures, Stress