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Mindfulness for adaptation to analog and new technologies emergence for long-term space missions

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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.

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 on 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 2 months. 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 and 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.

Author contributions

BLR, CM-K, and MT drafted the manuscript. All authors contributed to the development of the selection of studies. BLR developed the search strategy and equation for the database. All authors read, provided feedback, and approved the final manuscript.

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Conflict of interest

The authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

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