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Optimise behavioural health and human factors research for deep space missions by classifying analogue scenarios and fidelity

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Future human space missions beyond low Earth orbit face significant challenges in understanding and managing astronaut behaviour and performance in extreme environments, with behavioural health remaining a critical knowledge gap. Ground research in analogue environments offers cost-effective means to address these challenges. Still, due to analogues' compromised fidelity levels, the findings derived from such activity may only sometimes be reliable, rigorous and transferable to human space exploration. We hypothesise that gaps in understanding human behaviour and performance could be significantly addressed by using analogues with higher realism, which can accurately replicate specific conditions and yield more relevant insights to better inform future space missions. This paper takes a behavioural health approach to future spaceflight and evaluates analogue scenarios in such a perspective, to ensure the ecological validity and reliability of behavioural health research outcomes. Furthermore, we emphasise the functional-contextual importance of the features of analogue scenarios to resemble the complexity of current and/or future human space mission scenarios in terrestrial settings. Building on previously published research, we introduce the Extended Feature Classification System of Analogues (EFCSA) to identify analogue scenarios with greater realism. It evaluates the analogue's fidelity level based on contextual and human factor features. Features themes include isolation, lack of resupplies, element of exploration, environmental conditions, biopsychosocial impact, and skill expertise, among others. Based on the EFCSA, we preliminarily identified a range of analogue scenarios into Low-, Mid-, and High-fidelities and introduced the term "Peak-fidelity". The latter (such as wet cave exploration, and submerged cave system exploration and camping) and high-fidelity scenarios (saturation diving/underwater habitats, polar expeditions, polar overwintering, and submarines) offer the greatest fidelity in replicating space features with further potential. Mid-fidelity activities include technical diving (open water/pools) and dry cave exploration and camping. Low-fidelity activities include recreational diving (open water, <40 m), marine expeditions and sailing, piloting, parabolic flight, desert-based surface analogues and mountaineering expeditions. It is important to highlight that these results do not diminish the utility of other analogues; instead, the EFCSA helps to identify specific purposes for which analogues are useful, and serves as a means to improve analogue realism.

KEYWORDS

human space exploration, analogue fidelity and realism, behavioural health and human factor research optimisation, functional-contextualism and expertise, arctic, antarctic or polar expeditions, dry and wet caving, and technical diving

1 Introduction

Future human space missions aim to explore outer space beyond the Low Earth Orbit (LEO), starting with the Moon (ESA, 2018), with an overall target to establish and maintain a permanent human presence on the surface of other planets and even on asteroids (International Space Exploration Coordination Group, 2018). Such ambitious endeavours come with many significant challenges (Zubrin and Clarke, 2011). Many of these challenges are strongly associated with human factors, particularly uncertainties related to human behaviour and performance (Kanas and Manzey, 2008; Vakoch, 2011).

Key hazards of human spaceflight include space radiation, isolation and confinement, distance from Earth, altered gravity, and hostile/closed environments. Each of these hazards uniquely affects human factors and behavioural health in deep space missions. However, there remains a significant gap in comprehending the behavioural health complexities astronauts may face, particularly with respect to how these hazards interact and manifest over prolonged missions (Whiting and Abadie, 2024; Childress et al., 2023).

The past decades of human spaceflight have highlighted the complexities of maintaining human health during crewed International Space Station (ISS) missions. Various risk mitigation strategies, such as stringent astronaut selection criteria, procedures and standards of care, have been developed to ensure human safety and sustained human presence in LEO, which is now considered a relatively well-understood environment for human activities in space. These strategies, along with the ISS mission architecture, orbit dynamics, and existing space infrastructure, have allowed a focused approach to human factors and performance specific to LEO needs. However, this necessarily focused perspective has come at the expense of developing broader knowledge and strategies to support future human activities beyond the LEO. Such future needs in deep space are persistent knowledge gaps that demand a different approach to human factors and behavioural health from the one used on LEO-based ISS operations. Effective human health and performance management in deep space will likely require innovative strategies to meet the challenges of more distant and prolonged missions, such as Earth-independent operations and time delays in communication. Addressing these challenges will require a substantial re-evaluation of operations, infrastructure, and behavioural support (Schlosser and Cinelli, 2022a).

Narrowing these knowledge gaps and considering the unexpected implications of unknown factors is essential for advancing our understanding of the potential challenges associated with future space missions beyond LEO (Pagnini et al., 2023). Ground research and preparations are strategically important, as they enhance our understanding by simulating specific aspects or phenomena that occur in space. Additionally, conducting investigations on Earth through analogue studies provides a space-like context, offering results at a lower cost than space-based research, particularly in studying human behaviour and performance (Schlosser and Cinelli, 2022a).

This paper evaluates behavioural health research in space exploration to understand the existing gaps between current and future space missions and analogue missions. It aims to identify suitable analogue scenarios to optimise research in human behaviour and performance, as these behavioural factors are fundamental to the success of future space missions. We want to address a key question: how can we replicate astronauts' expertise and the complexity of their tasks on the ground through similarly challenging human activities? And if so, in what context? We foresee the answer lies in creating or accessing environments that closely mimic space scenarios with experts responding to mission complexities and risks.

When it comes to future activities in space, we shall aim to uphold and bolster space analogue research related to behavioural health to produce research outcomes that are reliable, valid and repeatable in similar contexts (Decadi et al., 2018; Schlosser and Cinelli, 2022a; Schlosser, 2019; Cromwell et al., 2021), that is, to predict human behaviour with precision, scope and depth (Hayes, 2004; Biglan and Hayes, 1996). Hence, in this paper, we critically evaluate and.

a) raise awareness about the importance of behavioural health and performance concerning future space missions,
b) discuss the functional importance of challenge-as-context and expertise in human space exploration analogues,
c) identify the core features of suitable, high-fidelity space scenarios in relation to future space mission needs and
d) investigate current analogue scenarios based on those core features, and we identify high-fidelity space analogue contexts using the functional-contextual perspective on human behaviour and provide recommendations for analogue scenarios that meet these features.

This work leads to a framework, the Extended Feature Classification System of Analogues (EFCSA), or the Cinelli and Schlosser Classification, designed to support the scientific community in identifying analogue environments with enhanced realism, tailored to specific research objectives. By aligning analogue settings more closely with the conditions encountered in space missions, this framework aims to improve the ecological validity and applicability of findings in space health and behavioural studies.

To achieve this, the sections below: discuss and critically evaluate the importance of behavioural health in present and future deep space missions; evaluate realism in analogue missions studying behavioural health and review existing classification methodologies from a behavioural health perspective; reason for the implementation of the functional-contextualist perspective in analogue and human spaceflight; apply the functional-contextual approach to the feature classification system to take high-fidelity analogues' realism further; identify high- and peak-fidelity analogues and their role in behavioural health research; address and place recommendations to the limitation of current space analogues.

2 Exploring the importance of behavioural health in present and future space missions

Behavioural health has a mission-critical role in human spaceflight, with its impact expected to grow significantly beyond LEO and long-duration missions (which here refer to crewed space missions lasting longer than 6 months) (Decadi et al., 2018; Le Roy et al., 2023). Behavioural health covers all biological, psychological, and social (biopsychosocial) aspects, such as performance, team cohesion, mental health, autonomy, leadership, or resilience. Furthermore, the biological aspect extends to other related human factors such as physiology, neurology, medical parallels, psychiatry, ergonomics, operation, and even system design. Overall, behavioural health covers most biopsychosocial elements related to a crew member's adaptive or maladaptive behavioural functioning (Schlosser, 2023a; Pagnini et al., 2023).

As long as crewed missions are conducted under well-understood conditions and meticulously planned—such as those in LEO—most human health and performance challenges can typically be managed effectively and are controlled through careful selection, training, and operational procedures.

This relatively high level of predictability is thanks to the expert knowledge accumulated over previous decades of human spaceflight. However, controlling through astronaut selection, operational protocols, medical solutions, technology, architectural solutions, and other domains may no longer guarantee lasting behavioural health and performance results in deep space missions. Deep space missions run in new environments, where new challenges may require new approaches in operations because risks might not be addressed using approaches developed for LEO operations, such as real-time communications. As a result, future crews will need to be more autonomous and rely on their own skills, performance, and adaptive response to address hazards and risks (Antonsen L et al., 2019). Much research shows that mental health consistently predicts performance and productivity (de Oliveira et al., 2023; Lu et al., 2022; Nowrouzi-Kia et al., 2022; Hourani et al., 2006) in groundwork environments. It is very likely that mental health will have a similar importance in future deep space missions too (Antonsen L et al., 2019; Le Roy et al., 2023), as discussed in recent cognitive-behavioural interventions performed in space exploration pilot studies (Schlosser, 2023a; Schlosser, 2020a). However, psychological and behavioural matters arising in deep space missions may become more complex to tackle with the length of the mission (Le Roy et al., 2023). Acute and chronic changes in behavioural health should be anticipated to occur during deep space missions, regardless of the crew selected (Schlosser, 2023a; Le Roy et al., 2023). The psychological challenges developed over time could include various levels of mood disorders, anxiety, psychosis, sleeping and even personality disorders (Vakoch, 2011; Schlosser, 2023a; Jones, 2010; Le Roy et al., 2023), which can significantly impact mission-critical outcomes (Jones, 2010; Le Roy et al., 2023).

A long list of studies conducted on human subjects in Antarctica, Mars 500 and other analogues and human space missions show the detrimental effects of isolation and confinement environments (ICE) on behavioural health (Palinkas, 1991; Kanas et al., 2011; Sandal, 2012; Ushakov IB. et al., 2014; Wang et al., 2014; Gaffney et al., 2017; Sasahara et al., 2020; Brereton et al., 2021; Palinkas and Suedfeld, 2021; Le Roy et al., 2023; Patel et al., 2020). These findings underscore the need for medical, psychological and organisational adaptations of recruitment, training, operation and support of a future crew in an interplanetary mission (Decadi et al., 2018; Schlosser, 2023a; Ushakov IB. et al., 2014; Palinkas and Suedfeld, 2021; Gushchin et al., 2019; Schlosser, 2023b; Pagnini et al., 2023; Le Roy et al., 2023; Patel et al., 2020). However, the use of ground resources, including analogues, can only account for a degree of fidelity with human activities in space (Schlosser, 2021; Le Roy et al., 2023).

Factors such as total confinement, isolation, chronic stress, prolonged exposure to microgravity and radiation, and escalating levels of extreme threat and challenge encounters could potentially lead to new psychological conditions. For example, the potential for an unexpected mechanical failure that may not be repaired, an increasing sense of detachment from humanity on Earth and the original mission goals due to an increasing sense of confinement and isolation, or prolonged time spent in microgravity could alter the sense of body movement or tactile responses and vision (Torok et al., 2019; Gallagher et al., 2021) body image. This altered sensation might impact one's self-confidence, leading to potential challenges in critical operation situations among crew members. Additionally, radiation exposure could impact brain and nervous system responses, affecting behavioural adaptivity (Hupfeld et al., 2021; Pagnini et al., 2023). How can we effectively address or mitigate these biopsychosocial challenges over extended durations (Schlosser, 2023a)?

Whiteley and Bogatyreva (Whiteley and Bogatyreva, 2018) were commissioned by ESA to provide a comprehensive review of space analogue studies. They analysed polar expeditions and explorer diaries and interviewed Apollo and current astronauts. The authors collaborated with experts from three space agencies, the military, civilians, submariners, Antarctic explorers, and firefighters. This extensive effort aimed to gather insights from diverse real-world environments that parallel the conditions of space missions, thereby creating a detailed understanding of the psychological challenges faced in such extreme conditions.

The benefit of this work (Whiteley and Bogatyreva, 2018) lies in its systematic categorisation of psychological issues, resulting in the Psy-Matrix (Whiteley et al., 2008), which lists over 2,000 detailed situations grouped into 36 systematic challenge categories. Each category allows for the creation of scenarios to be used in analogue studies to challenge the crew and test the suitability of any tools designed to assist astronauts in future space exploration missions. The study (Whiteley et al., 2008) breaks down ambiguous categories like monotony into more specific contributing factors, such as environmental, social, and individual aspects. These factors are not limited to repetitive routines, lack of variety, and environmental sameness. By doing so, the study (Whiteley et al., 2008) makes these complex issues easier to communicate not just to psychologists but also to engineers and other professionals. The clearer breakdown of monotony-related factors helps professionals across different fields identify and address these challenges in practical ways. In the space sector, this structured approach allows for identifying and mitigating all types of stress factors, thereby enhancing the design of psychological support tools for future astronauts. The research also reviewed existing psychological support tools used in similar mission scenarios, providing a robust foundation for developing new support strategies, which could be applied in future simulation studies to create more realistic and effective training scenarios for astronauts (Whiteley et al., 2008; Whiteley and Bogatyreva, 2008). The development of the Embedded Psychological Support Integrated for Long-duration Missions (EPSILON) system, based on these findings, offers a comprehensive toolset for the prevention, monitoring, and resolution of psychological issues. By using data from analogous environments and systematically arranging solutions into the Psy-Matrix, future missions can better prepare for and address the psychological stresses of long-duration space travel, ultimately improving crew wellbeing and mission success (Whiteley and Bogatyreva, 2018; Whiteley and Bogatyreva, 2008).

To date, space agencies mainly use preventive mitigation approaches to eliminate or reduce the impact of hazardous and negative outcomes on astronaut behavioural health. Yet, the emphasis on preserving human health is expected to significantly shift towards shaping acute interventions beyond LEO in deep space missions (ESA, 2018; Schlosser, 2019; Cinelli, 2023; Pagnini et al., 2019; Schlosser and Cinelli, 2022b). Even though it is paramount to maintain the crew's behavioural and physical health, team cohesion and performance during any mission, especially in deep space missions, published literature says very little about behavioural health solutions and the psychological interventions to adequately prepare the crew for encountering them (Schlosser, 2023a).

As early as 2013, Moonmaw (2013) pointed out that we should invest resources into identifying the appropriate cognitive behavioural approaches to aid astronauts in space travel. According to Schlosser, modern Process-based Cognitive-behavioural interventions should be emphasised (Decadi et al., 2018; Schlosser, 2019; Schlosser, 2023a), for example, Acceptance and Commitment Therapy (Decadi et al., 2018; Schlosser, 2023a; Schlosser, 2024b), in addition to other mindfulness-based interventions, like Mindfulness-based Stress Reduction, Mindfulness-based Cognitive Therapy (Schlosser, 2019; Pagnini et al., 2019; Schlosser and Whiteley, 2022; Pagnini et al., 2023; Schlosser, 2024b) in astronaut training and mental healthcare. Such approaches are effective in treating various types of disorders (transdiagnostic) and are usable in various performance contexts (transtherapeutic) to tackle a wide variety of biopsychosocial challenges, including coping with difficulty and dealing with isolation (Schlosser, 2023a; Schlosser et al., 2021; Pagnini et al., 2023; Antonova et al., 2021; Schlosser, 2024c). Mental health is a particularly important human factor concerning mission-critical success; extensive research from ground scenarios (such as military and workplace) shows that mental health positively predicts performance and productivity (r = 0.38) (de Oliveira et al., 2023; Lu et al., 2022; Nowrouzi-Kia et al., 2022; Hourani et al., 2006).

While humanity is preparing again to take the next giant leap, a growing number of review papers discuss the future behavioural challenges of spaceflight (Schlosser and Whiteley, 2022; Schlosser, 2024b; Le Roy et al., 2023; Patel et al., 2020), but only a few aim to address how to solve these challenges (Schlosser and Whiteley, 2022). There are a small number of studies that passively assess mental health and performance, typically only in analogue contexts (for example, 15, 32–34, 52), and even fewer active intervention studies aim to maintain or increase behavioural health and performance in analogues to demonstrate the means how to supports astronauts in human spaceflight (Schlosser, 2023a). Very few studies exist assessing the underlying psychological and behavioural health factors of behavioural health in analogues (Schlosser, 2023a), and in human spaceflight (Schlosser and Whiteley, 2022; Schlosser, 2020a). Currently, there are multiple efforts running to explore how mindfulness training may contribute to astronaut behavioural health and performance onboard the ISS (Schlosser and Whiteley, 2022).

For future long-duration missions, far more research is needed to learn the factors affecting behavioural health to identify the means of preparing and supporting the crew and its members living beyond LEO in deep space sustainably.

The status of the research field is due to the following reasons: conservative risk assessments, existing approaches for selection and training of astronauts, the low number of astronauts considered in research studies results in mostly case studies or small sample studies, several different kinds of scientific approaches and methodologies across stakeholders, furthermore the research ethics naturally requires confidentiality and anonymity, among other reasons (Schlosser and Whiteley, 2022).

Analogues could serve as the ideal testing ground to overcome these boundaries, but only if high realism can be maintained; otherwise, it is difficult to see how knowledge of psychological and behavioural health factors is transferable to human spaceflight. As whilst a lot of research is available in other medical, military or other critical operational environments in these domains, this knowledge might apply with limitations to novel forms of human spaceflight (Schlosser and Cinelli, 2022a; Schlosser and Whiteley, 2022; Pieters and Zaal, 2019).

Due to the complex nature of human spaceflight, the authors of this paper stress the importance of not overlooking the impact and complexity of human factors, behavioural health and performance in operations and human health research, particularly when it comes to future deep space missions. In this paper, the authors account for several analogue scenarios and fidelity to explore the use of analogues with high realism in contextual and human factors features. Psychological health underlies all the key critical operational outcomes in space missions. This recognition is essential to ensure the safety and success of human activities beyond LEO through testing and validation. That is, finding the appropriate analogous research context to test solutions during ground preparations is crucial and offers comparably cost-effective solutions to arriving at conclusions in actual human spaceflight scenarios.

3 Understanding realism in analogue missions: classification and insights

While space simulations typically focus on replicating one or more specific aspects of a space mission, analogue missions are more complex activities that aim to simulate a wide range of elements of a real crewed space mission. They aim to support preparation and research by comprehensively representing the mission environment and the crew activities.

In the past, analogues were primarily used as platforms for risk mitigation, testing, and validation of products and deliverables with high Technology Readiness Levels (TRL), ensuring they were nearly ready for use in the operational environment of outer space (Keeton et al., 2011). Nowadays, it is becoming increasingly common to introduce low TRL technology into analogues. These platforms are now considered valuable for early testing and validation in relevant operational scenarios, proving proof of concepts, as well as for outreach, and other non-scientific purposes. This shift in usage underscores the evolving role of analogues in contributing to advancing space missions. Consequently, discussions about the fidelity or realism of analogue missions are becoming more common to better understand the type of operational environment they attempt to reproduce.

A mission's realism, or fidelity, depends on the close interdependence of its objectives, operations, and scientific activities, collectively defining the scenario. This realism is achieved by aligning the mission's scientific contributions, implementation methodology, and operational value. Mission design encompasses the planning and execution strategies that simulate the conditions of actual space missions. It includes elements such as the selection of objectives, procedural methods, and the operational environment. The design of the mission is crucial in establishing its fidelity, as it ensures key similarities with a real crewed space mission, thereby validating its effectiveness as an analogue (Schlosser and Cinelli, 2022a; Cromwell et al., 2021).

Unless space agencies are directly involved, replicating the design of space missions in analogue scenarios is significantly constrained by available resources. This limitation has led to the development of new approaches to mission design aimed at overcoming the shortcomings of current methods that do not meet space agency standards. Consequently, the variability in mission design, which serves as the foundation for analogue missions, often makes them non-reproducible and challenging to compare. This inconsistency complicates the assessment and comparison of outcomes across different analogue missions. As a result, the scientific validity of research conducted in analogue missions may be questioned if the studies run in the mission do not specify details about the mission's design, safety and other critical factors, particularly those related to psychological and behavioural health (Schlosser and Cinelli, 2022b).

There has always been interest in developing tools or systems to navigate the potential of analogues. In 2011, NASA's Behavioral Health and Performance Element (BHP) developed an Analogue Assessment Tool (AAT) to identify optimal analogues—characterised by high fidelity, accessibility, and feasibility—for research to test and validate products and deliverables for future long-duration space missions (Keeton et al., 2011). The analogues and space scenarios accounted for in this study are the ISS, Antarctica–McMurdo, Antarctica–Concordia, Antarctica–South Pole, Antarctica–Antarctic Search for Meteorites program (ANSMET), NASA Extreme Environment Mission Operations (NEEMO), Haughton-Mars Project Research Station/ Devon Island (HMP), Desert Research and Technology Studies (DRATS), Everest, Pavilion Lake and the Pacific International Space Center for Exploration Systems (PISCES). In this study, these analogues are to be used before deploying products and deliverables in resource-constrained flight environments, particularly for high TRL efforts requiring final validation. The tool assists investigators in evaluating specific study needs against analogue characteristics, ensuring the best fit to address research gaps and mitigate risks. This systematic process objectively compares and selects the most appropriate analogue for each investigation.

The effectiveness of the AAT (Keeton et al., 2011) may vary for investigators outside of BHP, for example, due to limited global access to the analogues referenced in the tool. Additionally, the tool does not provide detailed information on the mission design of these analogues, which could affect research outcomes. Originally designed for NASA-led activities, the tool is geared towards contexts with high realism in mission design, which might only partially translate to other scenarios. Given the growing interest in analogues and the increasing number of studies conducted outside of space agencies, there is a need for a tool that any investigator can use to identify the most appropriate analogue for their activities.

In line with NASA BHP AAT's efforts (Keeton et al., 2011), the General Feature Classification System of Analogues (GFCSA) (Cinelli, 2020) offers an overview of existing analogues and their typical features, drawing connections between space analogues and human space missions. This classification emphasises contextual features as an initial step in evaluating analogues' fidelity levels. Unlike AAT, this approach includes analogues with diverse operational contexts beyond established platforms like Antarctica and NEEMO. This classification system leverages contextual features to offer a structured framework, guiding investigators and candidates in understanding mission design and operations across various analogue scenarios relevant to their research. Although many analogue studies aim to support human activities on other planets, they often operate independently. This classification represents a crucial first step toward achieving greater interoperability among analogues.

The General Feature Classification System of Analogues divided analogues into low-, mid-, and high-fidelity missions, with a three-point scale within each level of fidelity called Class. Low-fidelity analogue missions include features of isolation, confinement, and extremity. Mid-fidelity analogues incorporate features such as a lack of resupplies of resources, life-threatening and hazardous environmental conditions, and the lack of possibility of immediate rescue. High-fidelity analogues also incorporate features that impose severe stressors and physiological stresses on crew members, such as high altitude or depth pressures or alternating light/dark cycles. The classification system highlights that numerous analogues may only fall between Class 1 Low-fidelity and Class 2 Mid-fidelity. While low- and mid-fidelity missions only focus on introducing operational stressors to crew members, high-fidelity missions involve operational stressors and stresses, and physiological adaptations (Cinelli, 2020).

TABLE 1 The updated version of the general feature classification system of analogues (GFCSA) (Cinelli, 2020).

	Low fidelity			Medium fidelity			High fidelity		
	Class 1	Class 2	Class 3	Class 1	Class 2	Class 3	Class 1	Class 2	Class 3
Features/Effect									
Isolation	None to Weak	Weak to Moderate	Moderate to Strong	Weak to Moderate	Moderate to Strong	Complete	Weak to Moderate	Moderate to Strong	Complete
Confinement	None to Weak	Weak to Moderate	Moderate to Strong	Weak to Moderate	Moderate to Strong	Complete	Weak to Moderate	Moderate to Strong	Complete
Extreme	None to Weak	Weak to Moderate	Moderate to Strong	Weak to Moderate	Moderate to Strong	Complete	Weak to Moderate	Moderate to Strong	Complete
Lack of resupplies	-	-	-	None to Weak	Weak to Moderate	Moderate to Strong	Weak to Moderate	Moderate to Strong	Complete
Life-threatening conditions	-	-	-	None to Weak	Weak to Moderate	Moderate to Strong	Weak to Moderate	Moderate to Strong	Complete
Failure to receive rescue	-	-	-	None to Weak	Weak to Moderate	Moderate to Strong	Weak to Moderate	Moderate to Strong	Complete
Environmental conditions	-	-	-	None to Weak	Weak to Moderate	Moderate to Strong	Weak to Moderate	Moderate to Strong	Complete
Altitude (from sea level up)	-	-	-	-	-	-	From sea level up to 5,486 m (18,000 ft)	From 5,486 m (18,000 ft) up to 7,620 m (25,000 ft)	From 7,620 m (25,000 ft) up
Depth (from sea level down)	-	-	-	-	-	-	From sea level to −30 m (−98 ft)	From −30 m (−98 ft) to −60 m (−200 ft)	From −60 m (−200 ft) down
Light/dark cycle							Negligible variations	Seasonal variations	Lasting for 6 months

In addition to the feature classification, Cinelli also designed a system to match analogues and spaceflight missions based on their duration. From a human behavioural health perspective, short-duration analogues often fail to capture the full impact of stressors such as confinement and isolation to the extent necessary for informing space medical research (Pagnini et al., 2023). Therefore, analogue missions, extending for a few weeks or months, are generally preferred for studying human factors and performance, as they provide a more comprehensive understanding of these stressors over an extended period (Mars500, 2024; Gushin et al., 2011; Ushakov I. B. et al., 2014). This way, Cinelli introduced a much-needed ranking system of crewed analogue missions sophisticated enough to compare analogues to relate them to crewed missions (Cinelli, 2020).

Table 1 presents an updated version of the original classification system (Cinelli, 2020), with feature levels revised to "none to weak," "weak to moderate," and "moderate to strong." This provides a range of fidelity that can be further validated with the involvement of professionals and experts in the field. The following paragraph provides preliminary results on this validation.

The reliability of any data obtained from analogues attempting to reflect human behaviour in ICE conditions beyond LEO is questionable because analogue missions frequently lack the behavioural health realism required to replicate such extreme conditions accurately. Therefore, it is also doubtful to what extent the data describing human factors obtained from one-off, low-fidelity, and short missions is valid and whether the skills and knowledge acquired from such activities are transferable and applicable to real and significantly more complex space missions (Schlosser, 2023b; Schlosser and Cinelli, 2022b; Schlosser, 2021).

Generally, human factors—especially behavioural health and performance research—are underemphasised in analogue studies. While many fundamental questions about safety for LEO missions have been addressed, the ultimate goal of space exploration is to support human survival and resilience not only in LEO but also in deep space and beyond.

To tackle future challenges beyond LEO, human factor research should study how astronauts and analogue crews cope not only with isolated and confined environments but also with dangers of threat, microgravity, radiation, lack of supplies, and no immediate means of rescue (Cinelli, 2020; Schlosser, 2021). In this paper, from now on, we consider the term ICE to be inclusive of such features. From a behavioural perspective, such "contextual" factors should be basic components of analogue missions to evaluate their impact under high-fidelity scenarios. However, the GFCSA has not yet included such features, mostly environmental ones.

In addition to contextual factors, it is also important to consider human factor features such as the field expertise of analogue astronauts. This expertise should ideally match that of formal astronauts to ensure the validity of the simulation. In other words, the complexity of the skill set and training of analogue astronauts used in complex ICE scenarios should closely mirror those of astronauts who embark on real space missions. This ensures that the experiences and challenges faced during analogue missions accurately reflect those encountered in space, thus enhancing the validity and effectiveness of the analogue environment in preparing astronauts for their missions. Moreover, the level of autonomy granted to analogue astronauts, the duration and complexity of missions, and the fidelity of mission tasks also contribute to the overall realism of analogue missions (Cinelli, 2020; Schlosser, 2021). These factors collectively shape the effectiveness of analogue missions in simulating spaceflight conditions and preparing astronauts for the challenges they will face in space.

In social and behavioural science research, the issue of realism surrounds the concept of ecological validity. Creating analogues directly speaks to the issue of ecological validity, which contains two distinct but complementary aspects most research aims to achieve. First, ecological validity encompasses providing appropriate cues that are sufficiently similar to real-world stimuli so that reactions to them could be deemed as equivalent to how a person would react *in situ*, that is real-world generalisability. Second, and in the absence of such cues, the controlled situation a person is exposed to should engender outcomes that are close to identical to how they would react to a real-life cue (Kihlstrom, 2021). In other words, ecological validity should either guarantee that a given context is sufficiently close in appearance to reality (i.e., verisimilitude) and/or that this context could predict the relevant future behaviour of the individual (i.e., veridicality) (Suchy et al., 2024). However, as pointed out (Holleman et al., 2020), it is impossible to make general statements on whether a certain factor is fully generalisable to a real-world situation it wants to emulate. Instead, defining which aspects should be deemed equivalent would be beneficial. For instance, vvan Berkel et al. (2020) argued that four aspects should be considered: the similarity of environment, tasks, users, and scenarios. In relation to astronautics and analogue research, these are the analogue environments, the operational activity, the field experts and/or analogue astronauts and the mission design in which the analogue is performed.

4 The functional-contextual importance of expertise in studying behavioural health and performance in analogue missions

Different actions have different functions in different situations, and they can lead to different success outcomes under different circumstances. In other words, human behaviour is contextual.

That is, a behaviour's functionality is entirely dependent on whether the response action carried out *in situ* ends up being adaptive or maladaptive in that given context. While navigating through challenges and difficulties, the sequence of adaptive or maladaptive actions and resulting learning experiences add up to expertise about handling the relative context and forming a coping strategy. Complex scenarios lend people exceptional challenges and opportunities to address the problem with contextually functional behaviour. Whether this contextually functional coping behaviour is adaptive or avoidant, during the time of challenge, it is definitive to the individual. The learned behaviour is functional in the original historical context; however, it may not be in another context. Consider here an example where fear allowed a person to act quickly and adaptively in a car accident; however, months after the accident the individual still maintains a fear of driving.

Adaptive coping allows individuals to remain behaviourally flexible and functional towards what matters for them in a given context despite experiencing a degree of difficult private events, that is, they are psychologically flexible and behaviourally adaptive and resilient (Schlosser, 2024a). Comparably, sequences of maladaptive, counterproductive, or avoidant behaviours in the longer run lead to unfavourable outcomes and result in the inability to cope, become dependent, unsuccessful, or experiencing "stuckness", that is, behaviourally rigid and psychological inflexible (Functional-contextual Skill-acquisition Model, FCSAM) (Schlosser, 2023a; Schlosser, 2024a). The utility of a skilful coping strategy is translatable into space exploration too, such as the ability to cope and develop domain-specific expertise to adapt to (or within) the context when dealing with adversity, in other words, to maintain behavioural adaptivity, psychological flexibility, and resilience (Schlosser et al., 2021; Schlosser, 2024a; Pagnini et al., 2024).

The FCSAM (Schlosser, 2023a; Schlosser, 2024a) states that the level and quality of our skills develop through stages, with each given behaviour being functionally and contextually decisive in the skill's developmental process. Learned behaviours may be contextually adaptive or maladaptive, as they are functional only in a situation-specific way. The learned behaviour needs to be moulded to the situation (or context) in order to maintain its functionality. This process of learning through maladaptive or adaptive responses develops across events and eventually thought stages as a direct outcome of the friction occurring between the context and the actor within the context. This way, it is possible to develop increasingly rigid responses when a task or event is too difficult or heavy, as well as to develop highly adaptive, flexible and resilient actions too, when a person experiences optimal difficulty that aligns with the individual's existing skillset to respond and cope with the event. Ultimately, these processes are continuous in life and events are inseparable from their historical contexts, and contribute to the individual's life as mental distress, stuckness or eventually ill-health, or contrarily mental wellbeing and productivity.

The FCSAM model combines and builds on the Dreyfus model of Skill-Acquisition (DSA) (Dreyfus, 2002; Dreyfus, 2004), Csikszentmihalyi's Flow state of optimal experiencing (Csikszentmihalyi and Csikszentmihalyi, 1988), and the Psychological flexibility model in Contextual Behavioural Science (CBS) (Biglan and Hayes, 1996; Hofmann and Hayes, 2019). The DSA argues that skill expertise is acquired through five stages: novice, competence, proficiency, expertise and mastery, being true to any skill-related activity. The DSA argues that as the learner becomes skilled, the learner depends less on abstract rules and principles, but more on concrete experience, where an expert is able to flexibly adjust to novel and unexpected scenarios. The Flow model describes an optimal experience, where the combination of challenge and difficulty requires a task performance that can be matched with one's skill expertise. It can lead to intrinsic motivation, deep focus, enjoyment, total involvement, loss of sense of time and self, learning, further mastery, and peak performance output. CBS is a branch of psychology that approaches human behaviour from a scientific angle: it aims to predict behaviour and psychological phenomena based on its functions in the context of evaluating fundamental psychological processes, like psychological flexibility and its elements. Psychological flexibility means the ability to persist or change in behaviour towards valued outcomes despite difficult private experiences, for example, fear, rumination or physical pain (Biglan and Hayes, 1996; Hofmann and Hayes, 2019). Like the original Dreyfus' model of Skill-Acquisition (Dreyfus, 2002), the FCSAM model also translates to any behaviour or skill, including coping, mental health, performance, skill expertise, or potentially any behaviour or cognition. For example, an individual can only experience the degree of involvement (or psychological flow) in his tasks based on his skill level and expertise functional in that context. Tasks of too high complexity unmatched with expertise would lead to psychological inflexibility, the inability to act towards valued ends due to too challenging private experience, for example, stuckness, or lack of self-esteem. Tasks that are too simple compared to one's respective expertise could lead the individual to boredom, not being able to find involvement in and engagement with the task at hand. However, when the optimal level of task difficulty and skill matches each other, the individual experiences psychological flow and flexibility, knowledge and skill development, and joy through attending to the task adaptively (Schlosser, 2023a; Dreyfus, 2004; Csikszentmihalyi and Csikszentmihalyi, 1988; Kashdan and Rottenberg, 2010; Schlosser, 2024a).

In CBS, to maximise prediction, the researcher must aim to target and influence manipulable variables in one's natural context "with precision, scope, and depth" (Hayes, 2004; Biglan and Hayes, 1996). Hence, any training or intervention delivered (for example, mental health promotion, astronaut training, counselling, therapy, leadership development, organisational development, among others) should occur in the relative natural environment of the individual (Hayes and Brownstein, 1986). Regarding our current capacities in space exploration, this means studying human behaviour in contexts that show realism (high-fidelity) to space exploration, that is, simulated or analogous environments and that share synergies with relevant aspects of the target space environment (Schlosser, 2024a).

Hence, we must argue that naturally occurring challenges lend a critical contextual angle to human space exploration research: (A) Testing the outcome of an intervention within a deeply relevant and important context to an individual lends greater realism to the research carried out; (B) Training people who perform in challenging contexts teaches them adaptable, experience-based strategies for future challenges, therefore knowledge is tangible and reusable in new upcoming situations in similar contexts; (C) It allows the researcher to examine individual/team performance and mental health in response to the challenge, that is, the context allows the researcher to examine functional responding while studying and understanding the underlying psychological processes (Schlosser, 2024a). It is worthwhile to point out (D) that space analogue conditions are significantly more cost-effective and have fewer risks than alternative contexts compared to outer space infrastructure (Keeton et al., 2011). This is another important reason why we must improve the realism of analogues and seek out, design and study behavioural health in high-fidelity analogues of space exploration (Schlosser and Cinelli, 2022a; Cinelli, 2020).

The number of analogue missions accepting research proposals has grown in recent years, with a greater opportunity to submit proposals for short-duration analogues, which tend to offer more flexibility and less stringent requirements. However, "fast-track" analogue behavioural research often evaluates human behaviour and psychology using cross-sectional designs typically acquired from low- or mid-fidelity analogues. Individuals or teams are rarely evaluated closely in their professional performance context. At the very least, analogue research should apply longitudinal designs or preferably (elements of) randomised-controlled trials capable of establishing temporal and/or causal evidence.

Furthermore, research should evaluate underlying psychological variables in relation to the desired outcome variables and should measure the impact of controlled conditions within a relevant high-fidelity context. Examples of similar studies include communities living in isolation in a remote station to carry out scientific experiments (Schlosser, 2023a; Pagnini et al., 2024), people being under confined quarantine during public healthcare emergencies, such as pandemics or epidemics (Schlosser et al., 2021), flight controllers directing the launch of an astronaut aboard the ISS (Schlosser, 2020a), or with cave-divers exploring submerged cave-systems or wet-caves (Schlosser, 2021).

We should evaluate the degree to which future behavioural challenges encountered in desert-based Mars/Moon analogue missions are equivalent to future challenges faced on the Moon, Mars or other space stations. The similarity between surfaces and the mere case of isolation may not be the only main challenges encountered. Instead, the first step towards reaching it may hold different hardships to overcome. We must create analogous scenarios that are suitable to incorporate the above points, and are more realistic in terms of context and challenges; hence, the data collected can be reliable and valid, thus, transferable to future space challenges (Schlosser and Cinelli, 2022b; Schlosser, 2024b).

Often, safety in analogues is open to personal interpretation and highly variable due to the lack of universal guidelines like those offered by space agencies. Such context leads most analogues to produce research that stands on its own and, consequently, has a low validity for execution in space. Handling isolated, confined, and extreme environments with a degree of threat does raise significant ethical considerations. Suppose such ICE scenarios already exist terrestrially and are regularly practised by respective field experts (in polar expeditions, offshore stations, working on boats or submarines, cave and dive exploration). In that case, the scenario should be utilised for space analogue research for the following reasons: it is tested and regularly practised, risks and threats are typically known, and hence, accidents can be prevented. Yet, it still allows plenty of unexpected and naturally occurring difficulties to handle. Field experts are exceptionally well-informed and experienced in such a situation to tackle such hardships. Further, such a high-fidelity analogue scenario requires crew members to adapt physically over the time they spend on the mission or expedition. Such a context may be extreme enough to mimic future long-duration missions and contextually adequate to study human behaviour, mental health, planning and decision-making (Schlosser, 2020b).

In such scenarios, we need to identify the levels of threat and danger that can have immediate, direct and indirect effects and permanent implications on individual and crew health and wellbeing with no apparent possibility of immediate rescue and access to further resources, however maintaining the safety and recovery protocols from actual space operations. Only field experts are well-suited for such tasks, similarly to an astronaut, who is also

TABLE 2 The features categories, subcategories and description.

Feature Classification of analogues			
Feature Categories	Feature Subcategories	Features	Feature description
Contextual Features (CF)	Situation	Environment	The environment where the activity is performed (W = underwater; G = Underground; O=Outdoor; I=Indoor; A = Aerial)
		Minimum duration	Possible shortest duration of mission (Hours = h; Days = d, Weeks = w; Months = m)
		Maximum duration	Possible length of the mission (Hours = h; Days = d, Weeks = w; Months = m, Years = y)
		Team size	Minimum team size constraints required for safe operations
	Contextual impact	Isolation	The team experiences social isolation from other groups
		Confinement	The activity runs with physical limitations
		Extreme	An environment exhibits traits that pose significant challenges or surpass the typical conditions for sustaining human life
		Mission duration	Long missions' duration
		Uninterruptible	The mission cannot be interrupted
		Monotony	Sensory monotony and deprivation
		Microgravity	Altered gravity or altered sense of gravity
	Level of threat	Lack of resupplies	Insufficient or scarcely available items, resources, or materials crucial to the mission. Resupply is limited or unavailable after beginning the analogue
		Limited resources	Limited resources available. It is not possible to persist in the conditions without resources for a long time
		Element of exploration	The sense of exploration involves venturing into remote or previously inaccessible locations, where participants may encounter subjective or practical exploration experiences
		Operational hazards	Operational hazards refer to medical situations or circumstances that pose a direct and imminent risk to an individual
		Failure to receive rescue	The team facing an emergency do not receive the expected or necessary assistance or intervention from rescue or emergency services
		Safe operations guaranteed	Conducting tasks or activities under the guidance of knowledgeable individuals within a controlled setting. This feature evaluates the expertise that professionals need to leverage to identify and mitigate risks, ensuring that the operation is carried out safely and effectively
	Environmental conditions	Environmental Impact	Continuous environmental factors are impacting activity and human health
		Ambient or atmospheric pressures	The pressure of the surrounding air or environment within the analogue habitat or simulated space environment is adjusted to simulate the pressure experienced in specific locations, such as space or various depths underwater
		Radiation	Environmental radiation exposure
		Temperature	Temperature appearing as an important factor in relation to human health and performance
		Depth	Underwater activity is measured from the water's surface down
		Altitude	Activity runs above water or on land, measured from sea level up
		Light/dark cycles	Alteration of natural light cycle and exposure
		Challenge of habitability	It refers to the challenge of establishing and maintaining a habitable environment
Human Factor Features (HFF)	Biopsychosocial impact	Physical effort	The physical effort involved or required to perform in the scenario
		Biophysiological impact	Significant biological or physiological challenges are involved
		Social impact	Presence of in- or out-group social stressors
		Psychological impact	A considerable amount of psychological stress

(Continued on following page)

TABLE 2 (*Continued*) The features categories, subcategories and description.

Feature Classification of analogues			
Feature Categories	Feature Subcategories	Features	Feature description
	Expertise and adaptation	Skill expertise	Considerable skill expertise and technical knowledge are necessary and available to field experts to cope with operational adversities and real-life scenarios. Skill expertise includes high-level knowledge and physical and psychological skills needed to perform within the context
		Technical requirements and expertise	Considerable specialised equipment and knowledge are necessary for practical application in real-life scenarios
		Risk mitigation through expertise	Significant field expertise is available to mitigate risks associated with the mission
		Planning required	Significant planning is required to carry out the activity
		Professional astronaut training	The activity necessitates professional training that overlaps with space agency astronaut training or daily activity
		Crew cooperation required	Significant cooperation is required to carry out the activity successfully
		Psychological flow	Enjoyable activity that demands peak performance, tailored to individual expertise levels to match task difficulty

meticulously selected and expertly trained to handle difficulties in space mission contexts (Schlosser, 2020b).

Expanding further on this perspective, in addition to the context, we should also consider the role of expertise in future human space missions. Astronauts are trained for years in encountering and successfully meeting mission-critical events, such expertise is not accounted for in most existing space analogues. That is, in astronautics, we match a challenge with the professional astronauts' skill expertise. Similarly, in space analogue behavioural health research, we should consider matching the crew's expertise with a matching challenge within the ICE context, so that the crew is appropriately equipped with the skill-expertise needed to persist in such environments. In high-fidelity analogues, where experts perform and overcome naturally occurring challenges, have higher realism than any other space mission analogues. In such scenarios, the behavioural data collected is more reliable, valid, and potentially transferable to current or future space missions (Schlosser, 2020b).

Hence, to account for these realisations and to ensure the success of future space missions, Schlosser and Cinelli (Schlosser and Cinelli, 2022b) recommend extending Cinelli's (Cinelli, 2020) General Feature Classification System of Analogues (GFCSA) with the relevant human factors and behavioural components to classify realism with more confidence by adopting Schlosser's Functional-Contextual Skill-acquisition Model (FCSAM) (Schlosser, 2024a) to optimise behavioural health and human factor research in analogue scenarios for future deep space mission contexts. We discuss the resulting Extended Feature Classification System of Analogues (EFCSA) below.

5 Introduction to the extended feature classification system of analogues (EFCSA)

Building on the FCSAM (Schlosser, 2023a; Schlosser, 2024a) and the GFCSA (Cinelli, 2020), the resulting EFCSA attempts to enhance fidelity analogues' realism by applying the functional-contextual approach to the feature classification system. This involves introducing behavioural and human factor components and further contextual features along with the existing ones. For further information, please see Table 2, where we report essential features to create a parallel with space missions.

The features are divided into two main categories: Contextual and Human Factor Features of analogues. These are further subdivided into Contextual Impact, Level of Threat, Environmental Conditions, Biopsychosocial Impact, and Expertise and Adaptation features. Each subcategory encompasses multiple design features that draw parallels between the analogue scenario and spaceflight. The "Situation" refers to the Environment, Minimum duration, Maximum duration, and Team size. The "Contextual impact" refers to Isolation, Confinement, Extreme, Mission duration, Uninterruptible, Monotony, and Microgravity. The "Level of threat" refers to Lack of resupplies, Limited resources, Element of exploration, Operational hazards, Failure to receive rescue, and Safe operations guaranteed. The "Environmental conditions" refer to the Environmental Impact, Ambient or atmospheric pressures, Radiation, Temperature, Depth, Altitude, Light/dark cycles and Challenge of habitability. The "Biopsychosocial impact" refers to Physical effort, Biophysiological impact, Social impact, and Psychological impact. The "Expertise and adaptation" refers to the Skill expertise, Technical requirements and expertise, Risk mitigation through expertise, Planning required, Professional astronaut training, Crew cooperation required, and Psychological flow. Please see Table 2 for the full list and supplementary materials.

Using the feature list shown in Table 2, we analysed scenarios and activities that are established space analogues or have the potential to become one. Most scenarios do not require a military background but demand highly specialised training and practice to ensure safe execution. We intentionally refrained from naming specific analogues. Instead, we reviewed analogue scenarios such as Recreational diving (open water, <40 m); Technical diving

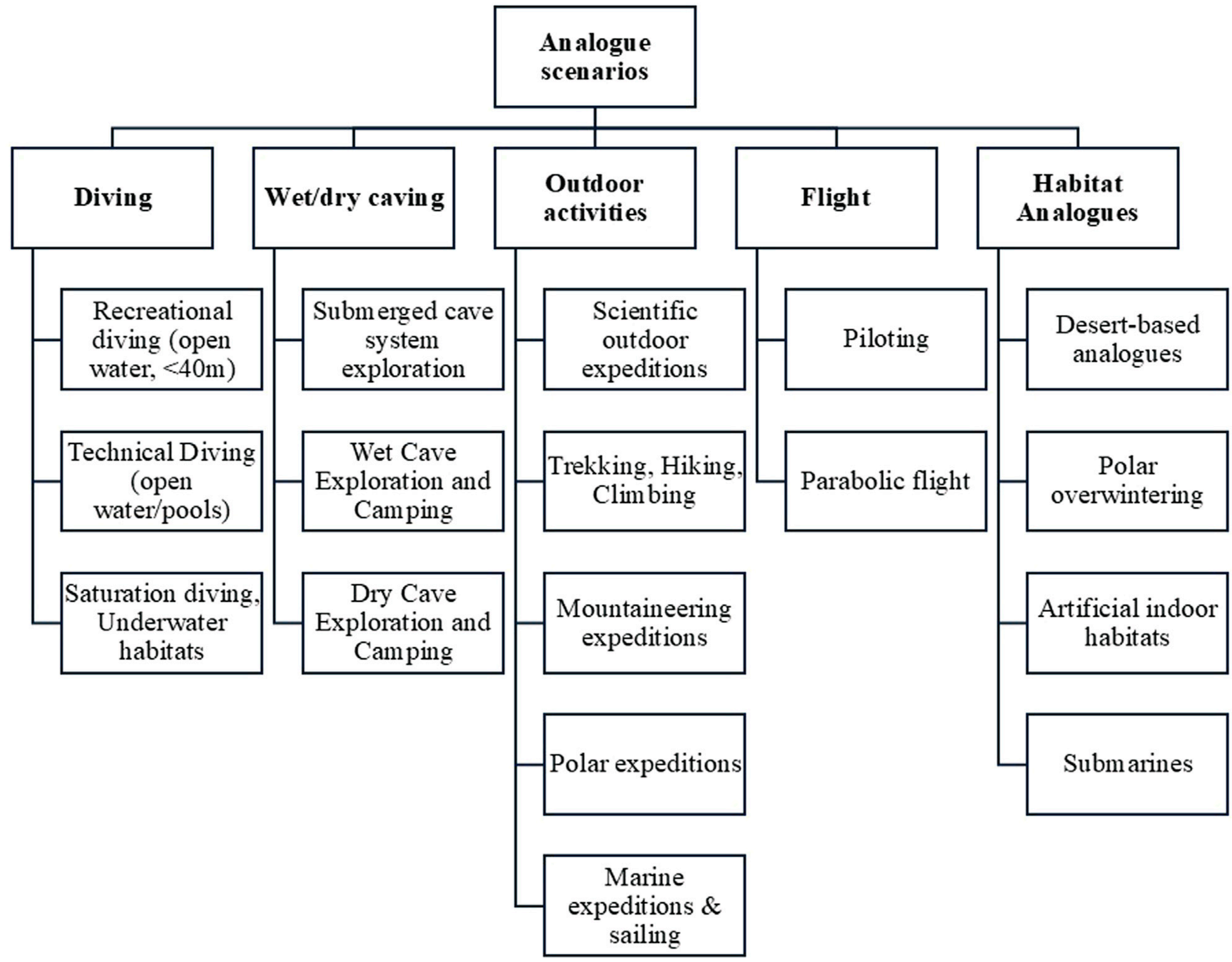

FIGURE 1
Analogue scenarios.

(open water/pools); Saturation diving/underwater habitats; Submerged cave system exploration; Wet cave exploration and camping; Dry cave exploration and camping; Scientific outdoor expeditions; Trekking, hiking, and climbing; Mountaineering expeditions; Polar expeditions; Marine expeditions and sailing; Piloting; Parabolic flight; Desert-based surface analogues; Polar overwintering; Artificial indoor habitats, and Submarines.

These themes cover a broad range of analogue scenarios but do not represent an exhaustive list and were reviewed in a generalised manner without accounting for specific cases or unique scenarios associated with each activity; please see a summary of these in Figure 1.

Using the feature list shown in Table 2, we assessed each analogue individually. The presence of a feature with the analogue scenario was rated between 0 and 4 (0 = no presence of feature; 1 = weak presence of feature; 2 = moderate presence of feature; 3 = strong presence of feature; 4 = complete presence of feature), with the exception of the "Situation" Feature Subcategory, which are merely a characteristic description of features. A five-point Likert scale was applied to all other features ranging from 0 to 4. This is a common methodological approach in behavioural science and psychology that is appropriate at this early stage of the classification system. Each feature's scores are added to a cumulative score called Feature Complexity.

Higher Feature Complexity scores generally represent analogues with greater relevance to space scenarios and higher fidelity. Additionally, no weighting system was applied to prioritise one feature or group of features over another. All features were treated with equal importance, and the scores were calculated without any differential weighting.

6 Properties and interpretation of the EFCSA

The EFCSA is designed to highlight the most relevant analogue themes and serve as an example of how to report scoring for particular analogue scenarios. EFCSA was developed to provide a quantitative assessment of various analogue scenarios in a generalised manner. It reports preliminary results about the features of the analogue scenarios. Feature complexity refers to the total scores for contextual and human factors features

TABLE 3 The Extended Feature Classifications System of Analogues (EFCSA) with the analogue scenarios features are rated on a 5-point Likert scale. The acronyms and abbreviations used are the following. Feature Classification: Feature Categories (FC), Feature Subcategories (FS), Features (F), Feature Description (FD), Contextual Features (CF), Human Factor Features (HFF), Feature Complexity (F-CX). Analogue Scenarios: Recreational Diving (RDV), Technical Diving (TDV), Saturation Diving (SAT), Submerged Cave System Exploration (SUB), Wet Cave Exploration and Camping (WCE), Dry Cave Exploration and Camping (DCE), Scientific Outdoor Expeditions (SCI), Trekking, Hiking, and Climbing (THC), Mountaineering Expeditions (MNT), Polar Expeditions (PEX), Marine Expeditions and Sailing (MES), Piloting (PIL), Parabolic Flight (PFL), Desert-Based Surface Analogues (DSA), Polar Overwintering (POW), Artificial Indoor Habitats (AIH), and Submarines (SUBM).

Feature Classification of Analogues			Analogue scenarios																
			Diving			Wet/dry caving			Outdoor activities					Flight		Habitat Analogues			
FC	FS	FD	RDV	TD	SAT	SUB	WCE	DCE	SCI	THC	MNT	PEX	MES	PIL	PFL	DSA	POW	AIH	SUBM
CF	Situation	Environment	W	W	W	WG	WG	G	O	O	O	O	OI	A	A	O	O	I	WGI
		Minimum duration	h	h	h	h	h	h	h	h	w	w	d	h	h	d	m	d	w
		Maximum duration	h	h	w	h	w	w	m	m	m	m	y	h	h	y	y	y	m
		Team size	2+	2+	2+	2+	2+	2+	2+	2+	1+	1+	1+	6+	8+	4+	16+	4+	120+
	Contextual impact	Isolation	0	0	4	4	4	2	0	1	1	3	1	0	0	4	4	2	4
		Confinement	0	0	4	4	4	3	0	0	0	0	0	1	1	4	4	4	4
		Extreme	1	3	4	4	4	3	0	0	2	3	1	1	1	3	4	0	2
		Mission duration	0	0	2	1	1	1	0	1	2	3	1	0	0	1	4	2	2
		Uninterruptible	0	1	1	4	3	2	0	1	1	4	1	1	1	1	3	0	4
		Monotony	0	0	4	3	4	3	0	1	1	4	1	0	0	2	4	4	3
		Microgravity	4	4	3	4	4	0	0	0	0	0	0	1	4	0	0	0	0
	Level of threat	Lack of resupplies	1	1	2	4	4	2	1	1	2	4	1	1	0	1	4	0	1
		Limited resources	2	2	2	4	4	3	1	1	2	4	1	1	0	1	4	0	1
		Element of exploration	3	1	1	4	4	3	0	1	2	4	1	3	0	1	1	0	1
		Operational hazards	1	3	4	4	4	3	0	1	2	4	1	2	1	1	2	0	2
		Failure to receive rescue	3	1	3	4	4	2	0	0	1	4	1	3	1	1	4	0	3
		Safe operations guaranteed	2	2	4	4	4	3	2	1	2	4	2	3	3	1	3	1	4
	Environmental conditions	Environmental Impact	2	2	3	4	4	3	0	1	1	4	2	3	1	2	4	0	0
		Ambient or atmospheric pressures	3	3	4	4	3	0	0	0	0	0	0	2	4	0	0	0	4
		Radiation	0	0	0	2	2	2	0	0	0	1	0	1	1	0	1	0	2
		Temperature	3	4	2	4	4	0	0	1	2	4	1	0	0	2	4	0	3
		Depth	2	3	4	4	4	0	0	0	0	0	0	0	0	0	0	0	4

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TABLE 3 (*Continued*) The Extended Feature Classifications System of Analogues (EFCSA) with the analogue scenarios features are rated on a 5-point Likert scale. The acronyms and abbreviations used are the following. Feature Classification: Feature Categories (FC), Feature Subcategories (FS), Features (F), Feature Description (FD), Contextual Features (CF), Human Factor Features (HFF), Feature Complexity (F-CX). Analogue Scenarios: Recreational Diving (RDV), Technical Diving (TDV), Saturation Diving (SAT), Submerged Cave System Exploration (SUB), Wet Cave Exploration and Camping (WCE), Dry Cave Exploration and Camping (DCE), Scientific Outdoor Expeditions (SCI), Trekking, Hiking, and Climbing (THC), Mountaineering Expeditions (MNT), Polar Expeditions (PEX), Marine Expeditions and Sailing (MES), Piloting (PIL), Parabolic Flight (PFL), Desert-Based Surface Analogues (DSA), Polar Overwintering (POW), Artificial Indoor Habitats (AIH), and Submarines (SUBM).

Feature Classification of Analogues			Analogue scenarios																
			Diving			Wet/dry caving			Outdoor activities					Flight		Habitat Analogues			
FC	FS	FD	RDV	TD	SAT	SUB	WCE	DCE	SCI	THC	MNT	PEX	MES	PIL	PFL	DSA	POW	AIH	SUBM
		Altitude	0	0	0	0	0	0	0	1	1	1	0	2	4	0	1	0	0
		Light/dark cycles	0	1	3	4	4	4	0	0	0	3	0	0	0	0	3	0	4
		Challenge of habitability	0	0	4	4	4	3	1	1	1	4	1	0	0	1	3	1	4
HFF	Biopsychosocial impact	Physical effort	2	3	2	3	4	3	2	1	2	4	1	0	2	1	0	0	2
		Biophysiological impact	2	3	4	4	4	2	0	0	0	3	1	1	3	1	2	0	3
		Social impact	1	1	3	3	3	3	0	1	1	2	1	0	1	2	3	2	2
		Psychological impact	1	1	4	4	4	2	0	0	0	2	1	0	1	1	2	1	2
	Expertise and adaptation	Skill expertise	2	3	4	4	4	2	0	1	1	2	1	3	1	0	3	0	2
		Technical requirements and expertise	1	4	4	4	4	2	1	1	2	4	1	3	1	1	3	0	4
		Risk mitigation through expertise	1	2	4	4	4	3	1	1	2	3	2	3	2	1	3	1	4
		Planning required	1	3	3	4	4	3	0	1	1	4	2	2	2	1	2	1	3
		Professional astronaut training	3	4	4	4	4	3	0	0	1	1	0	3	4	1	1	1	3
		Crew cooperation required	3	3	3	4	4	3	1	1	1	3	2	1	2	2	3	2	4
		Psychological flow	3	3	1	4	4	4	1	1	1	1	1	2	3	2	2	2	2
F-CX			**47**	**61**	**94**	**116**	**116**	**72**	**11**	**21**	**35**	**87**	**29**	**43**	**44**	**39**	**81**	**24**	**83**

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calculated by summing the scores assigned to each subcategory. Please see Table 3 for the rated analogue scenarios.

It is important to note that while contextual features include 25 elements, only 21 were included in this analysis. The four subfeatures under "Situation"—environment, maximum and minimum duration, and team size—are logical variables and do not follow the same numerical scoring system as the other elements. As such, they were excluded from the scoring calculations.

In Table 4, percentages for Contextual Features (CF) and Human Factors Features (HFF) were calculated by dividing each row value by the maximum values in each category (84 for CF and 44 for HFF, respectively). Fidelity levels are expressed as both labels and corresponding numerical thresholds of feature complexity, calculated as the sum of CF and HFF scores. These scores were derived by multiplying 128 (the product of 32 metrics and the maximum cell score of 4) by the total percentage of each cell. Fidelity levels are categorised as follows: peak-fidelity corresponds to percentages above 80%, high-fidelity to percentages between 60% and 80%, mid-fidelity to percentages between 40% and 60%, low-fidelity to percentages below 40%, and very low-fidelity to percentages below 20%. To enhance clarity, percentages were also converted into absolute score thresholds: very low-fidelity corresponds to scores below 25.6, low-fidelity to scores between 25.6 and 51.2, mid-fidelity to scores between 51.2 and 76.8, high-fidelity to scores between 76.8 and 102.8, and peak-fidelity to scores exceeding 102.8, up to 128. Table 4 presents a comparative analysis of various analogue scenarios, categorised into Diving, Wet/Dry Caving, Outdoor Activities, Flight, and Habitat Analogues, with fidelity levels determined by contextual and human factor features.

Note that fidelity levels are based on feature complexity, while domains compare the normalised percentages of CF vs. HFF. The scenario of "Wet cave exploration and camping" has 73 on CF (87%) and 43 on HFF (98%), or 116 combined (91% of total scores) out of 128 (100%). It is labelled as a Peak-Fidelity analogue scenario based on the feature complexity (CF + HFF) and is "Human Factors and Contextual Dominant" because the normalised percentages of both CF and HFF fall into quadrants where percentages are closer to 100%.

Another example is "Technical Diving." The latter falls into Mid-Fidelity because the sum of the feature complexity is 61 (48%), where CF is 31 scores (or 37%), and HFF is 30 scores (or 68%). Also, it is "Human Factors Dominant" because the normalised percentage of HFF is higher than that of CF.

Based on this analysis, activities classified as low-fidelity refer to scenarios such as recreational diving (open water, <40 m), marine expeditions and sailing, piloting, parabolic flight, and desert-based surface analogues, which exhibit limited feature complexity. Mid-fidelity corresponds to technical diving (open water/pools) and dry cave exploration and camping, which display moderate feature complexity. High-fidelity includes scenarios such as saturation diving/underwater habitats, polar expeditions, polar overwintering, and submarines, which involve advanced and intricate features. Peak-fidelity refers to submerged cave system exploration and wet cave exploration and camping, demonstrating the highest Feature Complexity levels in terms of CF and HFF. Finally, very low-fidelity refers to scientific outdoor expeditions, trekking, hiking, climbing, and artificial indoor habitats. These classifications provide insight into the relative complexity and fidelity of the scenarios analysed.

Figure 2 shows the relative percentages of human factors and contextual features of analogue scenarios based on the normalised scores, mapped across four quadrants: human factors and contextual dominant, human factors dominant, contextual dominant, and human factors and contextual non-dominant. Percentages of human factors (maximum = 44) and contextual features (maximum = 84) were plotted relative to their maxima. Bold black lines represent midpoints, calculated as the average of each category's maximum and minimum values, corresponding to 56% for the CF and 47% for the HFF. These lines divide the plot into four distinct quadrants.

In Figure 2, various markers are used to represent analogue scenarios, corresponding to their fidelity levels, to help readers understand the relationship between fidelity levels and the quadrants. Fidelity levels are determined by feature complexity, while domains compare normalised CF and HFF percentages. The markers are visual aids: circular markers indicate peak-fidelity, squares denote high-fidelity, triangles represent mid-fidelity, diamonds correspond to low-fidelity, and straight lines signify very low-fidelity. This distinction clarifies the visual relationship between fidelity and domain features.

This early analysis suggests 'Wet Cave Exploration Diving and Camping' (also known as push diving, which alternates between cave diving and dry-caving) and 'Submerged Cave Systems Exploration' are particularly promising for achieving peak-fidelity to crewed space missions. Due to their inherent complexity and associated risks, these themes provide an excellent context for in-depth studies of human behaviour and psychology under conditions analogous to those in space missions. 'Saturation Diving and Underwater Habitat Living also scored high and, due to the existing high-level industrial standards, depending on the context and objectives, they have significant potential to be further developed from high-to peak-fidelity analogues. Given the complexity of the analogue context and the expertise required for the activity, industrial saturation diving shows strong potential to resemble current and future space missions more closely. For Peak and High-fidelity analogue scenarios, both CF and HFF were dominant, meaning that features represented high were represented in the upper right quadrant of Figure 2.

'Polar Expeditions',' Polar overwintering', and Submarines also achieved high scores on the classification system, indicating their status as high-fidelity analogues, showing further potential to improve realism. Mid-fidelity analogues had either CFF or HFF as dominant, but not both subcategories; these were 'Dry Cave Exploration and Camping' and 'Technical Diving in Open Water or Artificial Pool'.

Notably, popular desert-based analogues and artificial isolation facilities scored lower than expected. Along with Recreational diving, Mountaineering Expeditions, Marine Expeditions and Sailing, piloting, and parabolic flight, Desert-based Analogues result in low fidelity, being no dominant in CF or HFF. At the same time, Artificial Indoor Habitats, Trekking, hiking, and climbing, and scientific outdoor expeditions are very

TABLE 4 Comparative analysis of analogue scenarios and respective fidelity levels in contextual and human factor features of the EFCSA. The acronyms and abbreviations used are the following. Feature Classification: Feature Categories (FC), Feature Subcategories (FS), Features (F), Feature Description (FD), Contextual Features (CF), Human Factor Features (HFF), Feature Complexity (F-CX), Raw Data (RD), Fidelity Levels (FL), Quadrant (Q). Analogue Scenarios: Recreational Diving (RDV), Technical Diving (TDV), Saturation Diving (SAT), Submerged Cave System Exploration (SUB), Wet Cave Exploration and Camping (WCE), Dry Cave Exploration and Camping (DCE), Scientific Outdoor Expeditions (SCI), Trekking, Hiking, and Climbing (THC), Mountaineering Expeditions (MNT), Polar Expeditions (PEX), Marine Expeditions and Sailing (MES), Piloting (PIL), Parabolic Flight (PFL), Desert-Based Surface Analogues (DSA), Polar Overwintering (POW), Artificial Indoor Habitats (AIH), Submarines (SUBM). Fidelity Levels & Classification: Peak-Fidelity (PFID), High-Fidelity (HFID), Mid-Fidelity (MFID), Low-Fidelity (LFID), Very Low-Fidelity (VLFID), Non-Dominant (NDOM), Human Factors Dominant (HFDOM), Human Factors and Contextual Dominant (HFCDOM), Contextual Dominant (CDOM).

		Analogue scenarios																
		Diving			Wet/dry caving			Outdoor activities					Flight		Habitat Analogues			
FC	Unit	RDV	TD	SAT	SUB	WCE	DCE	SCI	THC	MNT	PEX	MES	PIL	PFL	DSA	POW	AIH	SUBM
CF	*%*	32%	37%	69%	88%	87%	50%	6%	15%	27%	69%	19%	30%	26%	31%	68%	17%	62%
	RD	27	31	58	74	73	42	5	13	23	58	16	25	22	26	57	14	52
HFF	*%*	45%	68%	82%	95%	98%	68%	14%	18%	27%	66%	30%	41%	50%	30%	55%	23%	70%
	RD	20	30	36	42	43	30	6	8	12	29	13	18	22	13	24	10	31
F-CX	*%*	47	61	94	116	116	72	11	21	35	87	29	43	44	39	81	24	83
	RD	37%	48%	73%	**91%**	**91%**	56%	9%	16%	27%	68%	23%	34%	34%	30%	63%	19%	65%
FL	*FL*	LFID	MFID	HFID	**PFID**	**PFID**	MFID	VLFID	VLFID	LFID	HFID	LFID	LFID	LFID	LFID	HFID	VLFID	HFID
	Q	NDOM	HFDOM	HFCDOM	HFCDOM	HFCDOM	HFCDOM	NDOM	NDOM	NDOM	HFCDOM	NDOM	NDOM	NDOM	NDOM	CDOM	NDOM	HFCDOM

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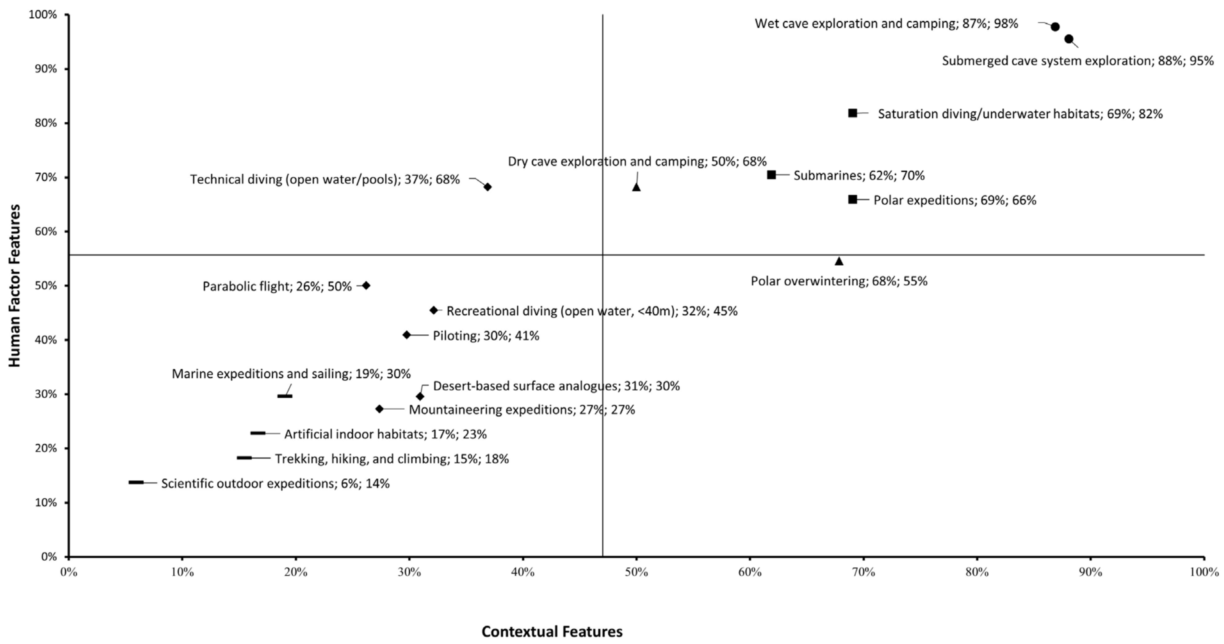

FIGURE 2
Analogue scenarios mapped on quadrants of human factors features and contextual features.

low fidelity, representing minimal contextual and human factor intricacy.

7 High- and peak-fidelity examples: forms of diving in astronaut training and analogue research

Analogues undoubtedly play an important role in examining different scenarios as they serve as a ground for research, technological solutions and the development of protocols. They also provide an opportunity to study human behaviour in ground-based extreme contexts; they mimic the environmental and contextual challenges of future space exploration missions with various success and levels of fidelity. However, running space missions on the ground also encounters limitations, for example, starting with the presence of gravity.

Several activities already use caving and diving separately to address current challenges in spaceflight. For instance, practising space suit dives in ESA's or NASA's Neutral Buoyancy Facility while working on replica parts of the ISS is a regular astronaut training activity. These exercises help astronauts familiarise themselves with floating and buoyancy, providing experiences similar to those encountered in microgravity during LEO spacewalks (Neufeld and Charles, 2015). Other significant underwater stationary analogues are the Aquarius Reefbase or NEEMO (Biglan and Hayes, 1996) and among other recently established underwater analogues such as Hydronaut or Aquanauta CE (Schlosser, 2023b; Schlosser, 2021).

On the other hand, the PANGEA (Sauro et al., 2023) and CAVES programmes (Sauro et al., 2021) are integral parts of astronaut training and the Human Space Exploration programme at ESA. During caving, astronauts practise skills essential for exploration, such as working together on geological experiments and familiarising themselves with confined, isolated, dark environments, exploration and scientific experiments. We currently have few scenarios where astronauts could practise cave or lava tube exploration; however, learning outcomes of human factors and behaviour in such missions are of enormous importance in future mission scenarios on the Moon or Mars (Schlosser, 2020b).

The utility of technical diving (for example, cave exploration diving, saturation diving, push diving, the alternation of cave diving, and dry caving) has yet to be fully explored in professional astronautics due to the dangers involved. Whilst cave diving is not without risks, given our terrestrial opportunities, saturation diving and cave-diving exploration activities may show high- or even peak-fidelity to future crewed spaceflight in terms of training, equipment and operational complexity, the expertise required, as well as the risks involved. These activities provide an analogous context for the scientific study of human factors and behavioural health, helping to prepare for future long-duration space missions.

There is a general tendency to avoid involving formal astronauts in complex and risky activities, such as technical diving scenarios. Instead, studying experts in technical diving—such as exploration cave divers, push divers, and saturation divers—can provide valuable insights without exposing astronauts to unnecessary risk (Schlosser, 2021). These professionals possess a high level of expertise and experience in their field, comparable to the specialised knowledge astronauts need in their own domains (Schlosser, 2023b).

Examining the behaviours and performance of skilled technical divers may be the way to investigate critical insights into human factors that are also relevant to future space missions (Schlosser, 2023b). Using high-fidelity analogues based on technical diving may allow us to explore human behavioural and health aspects in a controlled yet challenging environment (Schlosser, 2021). This approach may offer significant benefits for both scientific research and astronaut training. Leveraging the expertise of seasoned technical divers may help refine training protocols, equipment designs, and operational procedures, ultimately enhancing preparation for long-duration space missions (Schlosser, 2020b). This understanding is crucial for optimising crew cohesion, resilience, and performance in future space missions (Schlosser and Cinelli, 2022a; Schlosser, 2020b). By drawing parallels between these two domains, we can better prepare astronauts for the challenges they may encounter during long-duration space missions, ultimately enhancing future space exploration endeavours' safety, success, and effectiveness (Schlosser and Cinelli, 2022a; Schlosser, 2020b; Cromwell et al., 2021).

8 Discussions

Most space analogue missions do not achieve high-fidelity analogue of space exploration. While low- and mid-fidelity analogues can be useful for specific objectives, the reliability and validity of human factors findings, particularly those related to psychology and behaviour, may be compromised. Despite the use of rigorous methodologies in these studies, they often do not fully capture essential aspects of mission design. Current literature provides limited insight into how variations in mission design impact research outcomes, especially those involving humans. Additionally, unexpected variables that arise during missions can further complicate the reproducibility of study results (Cinelli, 2020; Schlosser and Cinelli, 2022b; Pagnini et al., 2024; Cromwell et al., 2021).

Utilising the EFCSA, as detailed in Table 3, in conjunction with the involvement of professionally trained experts in selected analogue themes, could enhance the quality of research conducted during analogue missions, particularly in studies related to human factors and performance.

It must be emphasised that the exact context, crew, expertise, tasks performed, seasons, presence or absence of Mission Control and Support facilities, procedures adopted, and all other features often vary across different analogue facilities or mission iterations. So, specific cases or variations of each activity could result in adjustments to these scores. Additional mission characteristics can enhance an analogue's fidelity level. Scores may also change based on specific mission objectives. For example, if the goal is to measure monotony, scenarios that involve isolation with either no activity or monotonous activity would be more suitable than those with a diverse range of activities. This illustrates how the research context should define the analogue scenario.

In any analogue, scientific objectives should be the starting point for the analogue mission's design, whereas in human spaceflight, mission objectives guide possibilities for scientific objectives to arise in exploration missions. This is an important difference between analogues and human space missions.

In this paper, we quantify analogue fidelity and arrive at the conclusion that higher fidelity analogues are generally more appropriate for research on human factors and behavioural health in future deep space missions. Higher fidelity analogues offer a more effective environment for studying the nuanced effects of space conditions on human behaviour and health by enhancing complexity and realism. This assumption builds on an understanding in line with previous research and space agencies' efforts, which utilise specific locations to produce research outcomes that can inform and mitigate the risks associated with human activities in space, as also indicated by NASA BHP (Keeton et al., 2011).

Notably, greater feature complexity in an analogue does not automatically make it the most suitable context (Keeton et al., 2011). In line with previous efforts (Keeton et al., 2011), we agree that the fidelity of an analogue is only a part of its value but does not define the value itself. The value of an analogue lies in both its fidelity and its appropriateness in relation to the specific objectives to be achieved. For example, studies about human factors in interaction with rovers might not necessarily need to be conducted in high-fidelity analogues. This could be due to environmental constraints (e.g., underwater vs underground) that might not allow the use of a rover, or because low-to mid-fidelity analogues can still provide informative insights about human interaction with a rover.

We must stress that scoring on the EFCSA does not diminish the value of analogues but highlights different features relevant to space exploration. It helps to identify whether an analogue is a good fit for measuring certain research objectives and assessing the fidelity of an analogue scenario. Typically, the data resulting from high- or peak-fidelity analogue missions have increased validity and reliability, therefore, represent space missions with greater realism and are more translatable when it comes to future space mission scenarios.

We also encourage professionals to identify means to improve analogue fidelity and realism with specific design features according to human factors and behavioural health research objectives.

9 Conclusion

New challenges of spaceflight could compromise human safety and require new behavioural solutions. This paper provides a method that advances knowledge to enable the future of spaceflight through analogue research. Below, we summarise some of the main conclusion points.

- We emphasise the significance of contextual and human factors features of analogue scenarios in accurately replicating the complexity, so the fidelity, of current and future human space missions. Such replication is essential for generating relevant insights into behavioural health and the associated biopsychosocial factors in terrestrial settings. Therefore, we recommend astronautics to embrace contextual behavioural science.

- Studies on human behaviour, human factors, and psychophysiology in analogues, onboard the ISS, or similar scenarios require careful consideration of their applicability across different analogue themes or terrestrial populations. Findings with the greatest potential for cross-domain transfer emerge from research conducted in well-defined, context-specific environments. These environments, termed high-fidelity and peak-fidelity analogue themes, enable the generation of robust and replicable data, enhancing their relevance beyond their original scope. Such tailored studies ensure a solid foundation for applying insights to diverse domains. In short, we recommend behavioural health and human factor research to be carried out in at least mid-fidelity, or preferably in high-, peak-fidelity analogues, with at least either Contextual Features or Human Factors being dominant, or preferably both, as identified by the EFCSA.
- It is important to note that certain behavioural and physiological features take extended periods to manifest, necessitating sufficient time for research to yield meaningful outcomes. Long-term studies in human behaviour and psychophysiology are essential for developing mitigation strategies and de-risking critical aspects of future crewed space missions through expertise. Future research should explore and define the appropriate duration of analogues based on scientific objectives and the highest possible fidelity level.
- We recommend engaging professionally trained experts in the analogue themes listed in Table 3 for high- and peak-fidelity scenarios. These professionals bring advanced expertise and experience akin to the specialised knowledge required by astronauts in their respective fields. Their involvement is essential for obtaining precise and ecologically valid data that is robust on human factors and behaviour, which is critical for advancing our understanding of human spaceflight.
- We suggest adopting the EFCSA for three purposes: (A) to identify the fidelity of an analogue; (B) to identify whether the fidelity level of an analogue is suitable for a research purpose, that is, whether the context is fit for the function, (C) to facilitate the assessment of whether the behavioural data obtained from an analogue mission are transferable to current and future human spaceflight, and (D) to develop analogues' fidelity through improved feature complexity.

Data availability statement

The original contributions presented in the study are included in the article/Supplementary Material, further inquiries can be directed to the corresponding author.

Author contributions

KS: Writing–review and editing, Conceptualization, Methodology, Project administration, Data curation. IC: Conceptualization, Data curation, Formal Analysis, Funding acquisition, Methodology, Project administration, Supervision, Validation, Visualization, Writing–original draft, Writing–review and editing. TW: Conceptualization, Resources, Writing–review and editing. LL: Conceptualization, Writing–original draft, Writing–review and editing. GP: Formal Analysis, Resources, Writing–review and editing. IW: Conceptualization, Investigation, Writing–review and editing.

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Conflict of interest

Author KS was employed by Humansys Ltd.

The remaining 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.

Publisher's note

Supplementary material

The Supplementary Material for this article can be found online at: https://www.frontiersin.org/articles/10.3389/frspt.2025.1391331/full#supplementary-material

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