Habitability Issues in Long Duration Space Missions Far from Earth

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Abstract. Living in space today means to stay at an altitude of about 400 km above the Earth surface, on the orbital International Space Station (ISS). In the '70s the man reached the Moon but a manned space exploration mission, beyond low Earth orbit and cislunar space, might significantly increase adverse psycho-physical effects on human wellbeing. Nowadays, a manned mission to deeper space, such as for example to Mars, is one of the greatest psychological challenge that has never been faced by the humankind. Due to the enormous distance between Earth and Mars, astronauts sent to Mars will be the first human beings who will lose a direct visual link with their Home Planet. Human responses to this and other extreme conditions that might be encountered during long duration missions into deep space are still unknown. In addition, the acute and long term effects of altered gravitational input on the central nervous system and their impact on sensorimotor and cognitive functions need to be clarified to assure maximum performance capabilities during spaceflight and planetary explorations. Our current knowledge on psychological and cognitive effects of orbital spaceflights or analogue environments is not sufficient to reliably assess the specific risks of human mission into outer space. New psychological challenges of mission to Mars will be analyzed with respect to three different areas: individual response and small crew interactions in isolated, confined, and extreme environments (ICE); human adaptation and performance in different gravity environments; concept and methods of psychological countermeasures. The needs of crew members to effectively and safely live and work in space are now referred to missions orbiting around the Earth and have been managed through specific human factors requirements applicable to the ISS. Future manned exploration missions need to reinforce these requirements to design an environment suitable for a safe stay during manned space missions far from Earth. The recommendations of astronauts who have experienced long term stays in space are collected and analyzed to be translated into requirements to be implemented in future space habitats. The analysis of what we have now and what is thought to be relevant to ensure crew wellbeing and performance during long term stays in space is a critical step to assure the success of deep space human missions.

Keywords: Space · Astronaut · Space habitats · Long duration space mission · Psychology

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1 Introduction

Science fiction books told us about travels to other galaxies with velocities larger than velocity of light, meetings with friendly aliens, star wars with ugly space monsters, etc. The beginning of the Space age (late fifties) opened the door to a magic box, full of scientific discoveries, made mostly by robotic satellites and spacecrafts. However, early Space trips clearly demonstrated that Space environment is extremely hostile to human beings. Man is not made for living in Space. Even if Space medicine, during the years since Gagarin flight, made an outstanding progress in supporting human presence at orbital stations, the radiation hazards and hypo magnetism problem are still opened issues without visible paths to their solution.

Also current research on human psychological and sociological effects of life in Space is based on on-orbit near-Earth experiences and therefore may have limited generalizability to long distance and long duration Space expeditions, such as a mission to Mars or to a near-Earth asteroid (which is currently considered by NASA).

In the case of Mars (or, more generically, in case of long duration spaceflights in deeper Space far from Earth), new stressors will be introduced due to the great distance involved in journeying to the Red Planet. For example, the crew members will be relatively autonomous from terrestrial mission control and will need to plan their work and deal with problems on their own. They are expected to experience significant isolation as the Earth becomes an insignificant dot in the heavens, the so-called Earth-out-of-view phenomenon, the effects of which are still largely unknown. Again, on the surface of Mars (as an example), the round trip communication delay time, depending on the relative position of Mars and Earth, ranges from 6,5 to 44 min approximately, increasing the sense of isolation [1].

The psychological effects of factors that are proper of autonomous long duration missions, such as Earth-out-of-view phenomenon, difficulties of communication, awareness of the impossibility to quickly return to Earth, confined habitat, isolation, etc. need to be analyzed and addressed with proper countermeasures.

Behavioral issues associated with isolation and confinement are currently studied by researchers on ISS or using terrestrial analogues. These studies collected extended evidence on emotional and psychological states and create a rank-ordering of behavioral observations addressing suggestions to help designing equipment, procedures, and activities to maintain mental wellbeing in future missions.

In a NASA experiment (HI-SEAS, Hawaii Space Exploration Analog and Simulation) [2], people living in isolation for a year to prepare for missions to Mars said "We were always in the same place, always with the same people". These kind of experiments are aimed to plan the methods and means of control and monitoring of the conditions of habitat and crew during long-term crew stays in confined and harsh environments.

The International Space Station (ISS), that now provides on-orbit research and technology development activities and, as an engineering test bed for flight systems, operations and technologies, is critical to future long duration missions.

The former approach adopted for maintenance of the ISS was based on a robust logistics system able to return large sub-assemblies for repair to ground. This choice was made early in the ISS design when the US Shuttle was the main cargo transportation system. It is now clear that after the retirement of the US Shuttle, the available download capability will be only a fraction of what is today. In addition, exploration missions outside Low Earth Orbit (LEO) will have very limited capability to return hardware to ground for repair and, in some cases, no possibility at all. This means that future interplanetary missions need to be self-reliant with respect to troubleshooting and repair and the ISS can be used now as a test bed to investigate and develop everything is needed for preparing future long duration missions far from Earth, including methods for in situ maintenance and repair.

The current Logistics scenario for the ISS is heavily constraining in terms of logistics, since it is based on "spare" concept: it foresees as baseline the ORU's (Orbital Replaceable Units) to be replaced on orbit using spares, but in case of failure it can be shipped back to ground either for repair or to be discarded.

In contrast, the development of interplanetary missions cannot rely on a maintenance scenario based on a spare policy. The interplanetary missions need to be self-reliant with respect to troubleshooting and repair, and the ISS can be used as a test bed to investigate and develop methods for in situ maintenance and repair.

Man is part of the system that must be made reliable to guarantee the success of the mission. Past and current manned missions/station (as the ISS) on LEO have relied on vehicles with rapid return capability for crew rescue. Either the spacecraft itself has this capability (e.g. Mercury/Gemini compared to Apollo) or a dedicated return vehicle (e.g. ISS, use of Soyuz). If return from LEO takes hours, return from the Moon takes days and return from Mars takes months. Therefore future long distance/duration missions will not have the capability to perform immediate crew return. The solutions implemented for in situ maintenance and repair become applicable to the man, since in this case it has to be considered a "fallible component".

Man is a critical system component that must be reliable. A "failure" of the "man" (intended as a component of the overall system) can compromise the success of the mission. Therefore, during long duration missions the crew need to undergo a strict program of preventive maintenance (physical, psychological, …).

Currently, the longest human spaceflight is that of Valeri Polyakov, who spent 437 days on orbit, in Space. All the longest spaceflights (see Fig. 1) were performed in orbit around the Earth (LEO).

CREW	COUNTRY	YEARS	STATION	NUMBER OF CONSECUTIVE DAYS IN SPACE
Valery Polyakov	Russia	1994-1995	MIR	437
Sergei Avdeyev	Russia	1998-1999	MIR	379
Vladimir Titov Musa Manarov	Soviet Union	1987-1988	MIR	365
Mikhail Koriyenko Scott Kelly	Russia United States	2015-2016	ISS	340
Yuri Romanenko	Soviet Union	1987	MIR	326
Sergei Krikelev	Soviet Union Russia	1991-1992	MIR	311

Fig. 1. The top longest space flights in history [3].

"*What are the most important habitability issues to be considered for long duration spaceflights?*". This question has been asked to Clayton Anderson, NASA astronaut who spent 152 day aboard the ISS.

In his answer he mentioned three different habitability elements:

- Window
- Private room
- Large room

Again, the statement "Windows are an essential part of vehicles and habitats for short and long-duration missions to optimize task performance and crew well-being" has been evaluated with the maximum score by another astronaut with experience of long term stay on orbit (6 months).

All these aspects represent the key factors to be taken into account to drive the design of the next habitats for the future manned Space exploration missions.

The challenge of Space habitat design is to create a living and working environment suitable for being recognised by the astronauts as "home"(the astronauts home in orbit), limiting the effects of the stressors as much as possible. It has to be comfortable, functional and safe enough to make astronauts feel well and thus perform effectively.

2 Psychological Highlights

2.1 Psychological and Cognitive Issues

A manned mission to deep Space, beyond LEO and cislunar Space, such as for example to Mars, is one of the greatest psychological challenge that humans have ever faced. Several stressors might condition the astronauts' mental state and their impact is expected to augment in human long-duration missions.

The main psychological issues are related to life in isolated, confined, and extreme environments (ICE). The most relevant of them comprise sleep problems, alteration in the sense of time, asthenia, career motivation, homesickness, anxiety, depression, and emotional problems [4, 5]. It is ascertained that astronauts are stressed and this represents an important variable because stress plays a crucial role in human behaviour, cognitive functions and emotions. During long duration spaceflights, chronic stress may result in decreased energy, intellectual impairment, decreased productivity, increased hostility, anxiety, sleep disorders, miscommunication, and impulsive behaviour [6]. The astronaut's mood has several psychological and behavioral effects. For example, a positive mood helps to minimize errors, make faster decisions, promote prosocial attitude and improve the state of physical well-being [7]. On the other hand, mood disorders negatively affect the quality of interpersonal interactions and interferes with normal operating conditions. For example, symptoms of asthenia include difficulty in concentrating, fatigue, and sleep disturbances [8]. A series of possible mental disorders might also potentially occur during long-duration mission - as classified according to the criteria of the DSM V (The Diagnostic and Statistical Manual of Mental Disorders) and/or the ICD 10 (International Classification of Diseases)- such as delirium (an alteration of consciousness that causes problems in concentration, focusing and having a coherent stream of thought), adjustment disorder (a severe and negative emotional response to a tragedy or significant change in one's situation, leading to considerable discomfort and significantly interfering with daily functioning of the person) and neurasthenia (a progressive negative psychological response to the isolation and rigors of a long-duration mission) [4, 9]. To prevent the emergence of severe psychological conditions, currently on the ISS, a psychiatrist or clinical psychologist has a weekly Private Psychological Conference (PPC) with the crew members. The information gathered during the PPC are used to periodically update the Integrated Medical Model (IMM), a statistically-based tool for forecasting possible risks for the crew health. It includes three behavioural categories: behaviour emergency, depression and anxiety. For NASA, behaviour emergency are behavioural or psychiatric conditions which can seriously jeopardize the mission, for example, a brief psychotic episode due to a tragic event like the death of a loved one or a disaster. Although until now, no emergencies have occurred during USA Spaceflight, their probability of occurrence increases with the increase of the journey length.

Importantly, in long-duration missions additional psychosocial issues are related to interpersonal relationships and group dynamics, including the need for privacy, the impact of crew diversity and leadership styles on small group dynamics. As reported by astronauts, participating in studies conducted on the ISS, adaptive and maladaptive features of ground-crew interactions, processes of crew cohesion, tension and conflict, language, cultural differences, gender biases represent additional psychosocial variables [10, 11]. As the duration of the spaceflight increases and the crew becomes more heterogeneous, psychological and interpersonal factors acquire a greater relevance. Extreme conditions such as prolonged confinement, isolation, and longer communication time delays will require the crew a higher level of interpersonal compatibility and capability to work autonomously, adapting to unforeseen challenges [12]. Thus, the team composition and the configuration of member attributes, become crucial factors to maximize the success of the mission. Good crew members' cooperation, coordination and communication are fundamental elements to increase team performance and teamwork [13]. Team performance and individual well-being are positively correlated with a good leadership that requires the knowledge of several leadership models [14]. The characteristics that may mitigate or exacerbate situations and influence team performance are homogeneity of personalities, shared interests, shared values and norms and other demographic factors such as common language, gender, expertise, age, ethnicity, and nationality [15]. Team functioning and the relationship with control personnel is often compromised by cultural differences and communication delay. Although not much attention is paid to the conflict between Mission Control Center (MCC) and spaceflight crew, the evidence is showing that this conflict might greatly impact the mood of astronauts [13].

Another important aspect to take into account in long-duration missions is the exposure to altered gravitational input, that greatly impact sensorimotor function. Microgravity is perhaps the most salient variable that affects the behaviour of individuals. Research has shown that microgravity in Space settings can affect a wide range of neurobehavioral outcomes. Such outcomes include cognition and mental imagery [16], neurovestibular function [17], posture and movement [18], and visual stability [19]. While vestibular and sensory outcomes in microgravity settings are fairly well understood, there is a relative lack of knowledge regarding how microgravity affects cognitive and affective functions. The impact of long-term microgravity exposure is even less understood; thus, microgravity constitutes a major risk that needs to be addressed in planning long-duration missions.

2.2 Habitability Issues

Beside the psychological issues described above, there are a series of additional stressors due to the environment and its habitability. Habitability refers to the features of the spacecraft which will take crew members to their destination and return them to Earth upon completion of their mission. The main habitability issues in long-duration mission far from Earth are currently identified as related to the lack of external view, the size of the habitable volume, and the lack of privacy.

Windows provide direct, non-electronic, through-the-hull viewing and are essential to mission safety and success, as well as to maintaining crew psychological and physical health and safety. They are essential for piloting and robotic operations, and permit safe viewing through hatches, stellar navigation, vehicle anomaly detection and inspection, and environmental and scientific observations. Importantly and in relation to psychological wellbeing, windows provide SA (Situational Awareness) of the external environment and support crew photography (a primary on-and-off duty activity of on-board crews). With respect to cameras or display systems, windows do not have the 'failure mode', that may not be operable during emergencies when most needed. A possible countermeasure that has been proposed is the inclusion of a window with a portal (~0.5 m^3 [1.7 ft^3]) in the common area and another window with viewing area to support mission activities when external views are required.

Another important factor of life in Space is related to the size of the habitable volume. The physical Space on ISS or in any Space vehicle is limited and social density is another stressor (NCR, 1998). Indeed, longer duration missions requires expansion in the physical volume of the habitable modules to accommodate mission tasks and personal needs. The total habitable volume for single crewmember and for the whole mission crew should be increased with duration, particularly if the mission is not able to be logistically resupplied. Due to the nature of the mission, the volume of the spacecraft will be necessarily small, although it has been shown that the volume of a habitat can impact a number of outcomes. For example, as discussed below, isolation and confinement in small volumes can lead to stress and other related outcomes as a result of sensory deprivation [e.g., 1]. Indeed, confinement, isolation, and stress that accompany a Space mission tend to increase with duration. This creates a psychological need for additional volume. A larger volume for the crew quarters than in the past, may provide privacy and restoration that will be needed in the long-duration exploration mission owing to the increased period of isolation and confinement. Quarters are clustered together to provide alternative social space and can be personalized (e.g. hanging pictures, varying positioning of bedding). Now in the ISS, the volume for each individual crew quarter is of 2.1 m^3 (74 ft^3). NASA is planning to increase this volume to 5.4 m^3 (190.70 ft^3).

Another important factor influencing the crew members' well-being is related to privacy. Also this aspect assumes a greater relevance as mission duration increases. Lack of privacy and the constant presence of other people have been reported to impair individual well-being and they are among the most adverse psychosocial stressors of long-duration mission. [20]. Given the increased need for privacy and the occurrence of territorial behavior under prolonged isolation and confinement, the provision of sufficient personal space and private quarters represents one of the most important psychological countermeasure. Personal space needs to be increased with mission duration, although this requirement may be limited by technical constraints.

Finally, additional stressors in the physical environment that is unique to Space include: a growing accumulation of garbage, limited facilities for sanitation, the need for constant vigilance. Currently, the noise and vibration of ISS are acoustic stressors, as well as the low level of illumination, that represents a photic stressor.

Most of the above listed factors are of some psychological importance, and represent important habitability issues to be addressed for the success of future of Space missions. Since a well-designed living and working environment can promote the crew's performance and well-being, the habitat design might also be regarded as psychological countermeasure during a Space flight.

2.3 Questionnaire

On the basis of previous reports and the published literature we built an ad hoc questionnaire aimed at collecting the opinion of astronauts on specific psychological and habitability issues during long-duration missions on the International Space Station (ISS). In the present paper we present preliminary evidence from data collected on one astronaut who experienced two long term stays on the ISS, with the intent to further develop this tool and administer it to an extended sample. The questionnaire on life in Space and its future development might provide useful insights into habitability requirements to be possibly applied in future artificial Space environments (i.e., Space stations). The semi-structured questionnaire, administered via email, was composed of 3 sections concerning: (1) *psychological well-being and crew members interactions* (17 items), (2) *human adaptation and performance in altered gravitational environment* (13 items), (3) *psychological countermeasures currently employed on the ISS, and possible interventions that might be useful to implement in future deep space missions* (7 items).

Section 1. Overall, the interviewee evaluates his experience with the other crew members on the ISS as excellent (item 1), reporting a great cohesion between crew members (item 2) and judging as very important having, once a day, some spare time (for example, at meals) to spend with them (item 3 and 4). The astronaut evaluates the common area on the ISS as very important (item 5) and ranks as follow the first four attributes (out of seven) that might improve its comfort (item 6): (1) a big window, (2) several small windows, (3) a dining table, (4) a bigger size of the room. In relation to psychological well-being, having one day a week to dedicate to other activities than the usual ones is judged of greatest importance (item 7).

Overall, his experience with the Mission Control Centre (MCC) was near to be excellent (scored 9 on a 10 points scale, item 8) and, the most relevant attributes of MCC members, selected among others (emphaty, listening skills, problem solving skills), were *encouraging attitude* and *supportive communication* (item 9). In accordance with previous reports, the astronaut confirms that the crew's motivation might decrease over time (item 10) and suggests as possible countermeasures, the possibility of having more frequent major operational events (e.g. EVAs) and video conferences (item 11). A greater autonomy of the crew members in planning their work schedule and/or priorities of nonessential tasks is judged as having only average importance (score of 5 on a 10 points scale). When asked to select among items expressing his impression about the work on the ISS he selects, among others (Tedious, Excessive, Stressful, Other), *Adequately distributed between members* and *Time demanding* (item 13). On item 14, the interviewee reports he spent most of his free time on the internet. Interestingly, and in line with previous reports, the possibility to see the Earth during a long-duration mission is deemed as being of crucial importance (score = 10, item 15). On the contrary, the presence of plants on the station environment is judged as less important (score = 5, as Food source and/or *sensory input*, item 16). Finally, when asked to express his opinion on possible countermeasures that might improve the interactions between the crew members and the psychological well-being on the ISS he underlines the relevance of selecting *'the right kind of person to serve as long duration astronaut and then ensure that the right crew complement is assigned'*.

Section 2. Interestingly, when asked how long it takes to adapt to move in micro-gravity (item 1), the astronaut reports that during the first flight it took a couple of days to be comfortable, 2 weeks to be more coordinated and perhaps 4-6 weeks to become graceful. While during his second flight, he largely adapted on the first day, and it took only few weeks to become graceful. The astronaut's response crucially indicates that motor skills learned during the first flight and relative neuroplastic changes were maintained over time (the time interval between the two flights was of 75 months). On items inquiring about any difficulty in anticipating the trajectory of moving objects (item 2), tactile sensitivity (item 3), Visuo-Spatial Orientation (item 4), and Body Representation (item 5), he does not report any change. The only sensory modalities in which he detected subtle alterations are smell and taste (score of 1 on a 10 points scale, item 7). In relation to Time Perception (item 7), the passing of time is defined as quick for the weeks and slow for the months and the lack of the 24-hour light-dark cycles does not seem to affect time perception (score = 1). On the other hand, a main factor that in the astronaut's opinion mainly affects time perception was the *constant work pace* (item 8). The current colors, labelling and lighting system are judged as being sufficient countermeasures to orient the crew members in absence of the gravitational input (item 9), while other factors that need to be improved (item 10) are the quality of air (score = 7) and the excessive noise (score = 6). The stowage (item 11) and the inventory system (item 12) need to be improved, and the astronaut's suggestion is by using the Radio Frequency Identification (RFID).

Section 3. Thirty minutes of Private Psychological Conference (PPCs), once every two weeks (item 1 to 3) is deemed to have a significant role on the crew's psychological well-being (score = 8). However, during a mission into deep Space, where PPC utility might be challenged by delayed communications, the alternative countermeasures are *increased social support between crew members* (score = 8) and *group cohesion* (score = 8) rather than *crew quarter privacy* (score = 5) or other activities (item 4). In terms of psychological well-being the current habitability of the crew quarters is judged as just above the average (score = 6) and the 4 main solutions (out of 8 possible items) for their improvement are reported to be the *privacy for personal communication*, *individual recreation (i.e., availability of compact entertainment devices), individual environmental control (e.g., adjustable lighting, temperature), space for stowage of personal items* (item 6). Finally, the out-the-window viewing capability in vehicles and habitats for short and long-duration missions (item 7) results to be an essential factor to optimize task performance and crew well-being (score = 10).

Taken together, these data confirm and further suggest the necessity to find solution to enhance external view, the space habitability size and privacy in the habitat in order to improve the chance of success of long-duration mission in deeper Space.

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