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To cite this version:

Giuseppe Ferraioli, Mickaël Causse, Stéphanie Lizy-Destrez, Yves Gourinat. Habitability of manned vehicules : the impact of human factors on future long duration human space exploration missions en route to Mars. Proceedings of 64th International Astronautical Congress, Beijing, China, September 23-27, 2013, 2013, Beijing, China. pp.1-8. hal-01851648

HAL Id: hal-01851648

https://hal.science/hal-01851648v1

Submitted on 30 Jul 2018

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To cite this version : Ferraioli, Giuseppe and Causse, Mickael and Lizy-Destrez, Stéphanie and Gourinat, Yves Habitability of manned vehicules : the impact of human factors on future long duration human space exploration missions en route to Mars. (2015)
In: 64th International Astronautical Congress, Beijing, China, September 23-27, 2013, 2013 - 2013 (Beijing, China).

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HABITABILITY OF MANNED VEHICLES: THE IMPACT OF HUMAN FACTORS ON FUTURE LONG DURATION HUMAN SPACE EXPLORATION MISSIONS EN ROUTE TO MARS

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August 3, 2013

Abstract

Placing humans in space for a long duration mission beyond Earth's neighborhood implies the design of a highly complex system to travel, live and work safely in the hostile environment of deep space. In order to identify all the constraints from both engineering and human sides, a meticulous system engineering approach has to be followed and the human sciences, including incorporation of ideas from artists, ergonomists and psychologists, have to be integrated in the very early stages of the mission design. Given the future human spaceflight destinations en route to Mars, i.e. deep space-habitats at Earth-Moon Lagrange points, lunar bases and asteroids, the main psychosocial and psychological issues are concerning the adverse effects of prolonged co-living and co-working in small groups, under conditions of confinement and isolation. With the aim to study the impact on habitability of latent and overt stressors, yielded by space flight missions, and to gain a deeper understanding of crew productivity and reliability, in socially risky situations and extreme environments, we conducted a survey involving a large sample size of participants, especially from naturalistic space analogues (Antarctic settings, caves extended exploration, remote sea-based oil drilling platforms, remote military outposts, drone pilots, Mars 520). The participants completed a questionnaire aiming to examine the effects of psychological, interpersonal and environmental factors on individual well-being and team performance. The data collected revealed the criticality of the several space analogues and helped to quantify the general statement which claims that no place on Earth can reproduce the exact extreme space conditions. The results suggest that the design of habitats and habitable structures for spaceships, extra-terrestrial planetary surfaces and analogue environments should include as many private crew areas as possible. The implementation of a continuous "in-flight" psychological support from the ground also appears to be a primary need. In addition, job specifications should be more team-work oriented, in order to avoid creating unwanted moments of isolation. Several other countermeasures are proposed for a successful integration of the human factors subsystem in the early mission planning. Finally, the paper suggests to focus on spin-off for terrestrial applications as further studies: our investigation found a strong synergy with the automation of dependent people with reduced mobility.

Introduction

Placing humans in space for a long duration mission beyond Earth's neighborhood implies the design of a highly complex system to travel, live and work safely in the hostile environment of deep space. Given the future human spaceflight destinations en route to Mars, i.e. deep space-habitats at Earth-Moon Lagrange points, lunar bases and asteroids, the main psychosocial and psychological issues are concerning the adverse effects of prolonged co-living and co-working [1] in small groups, under conditions of confinement and isolation. In planning any manned long duration mission beyond *Low Earth Orbit* (LEO) with unprecedented crew autonomy level, basic human needs cannot be understimated. Hence the integration of habitability issues (figure 1) in the very early stages of the mission design is essential to its outcome. This will result in a good prediction of the crew adaptation to deep space extreme conditions as well as the team-work and social interactions. The main challenges for a sustainable and long lasting human presence in the deep space concern the coupling of engineering and human factors subsystems. In this frame, the current paper lies on the frontier of the so called *Earth, machine and human* components.

Objectives

The global purposes of the present study are to:

- investigate the impact on habitability, i.e. the qualities of a mission that enable people to live and work in a safe and productive manner, of latent (permanent) and overt (linked to specific occurrences) stressors yielded

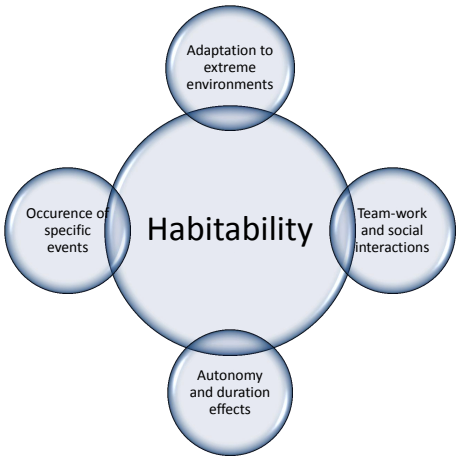

Figure 1: Habitability Issues

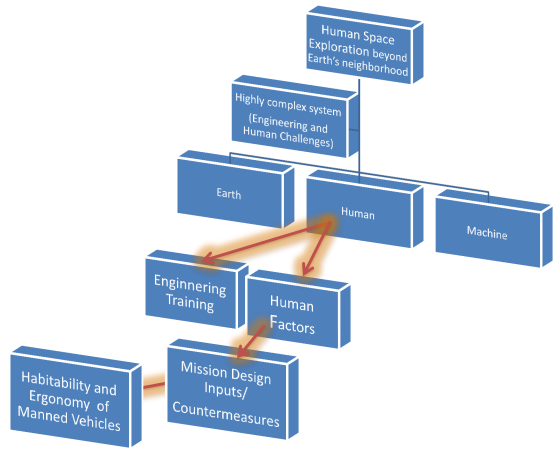

Figure 2: Systems Engineering Approach

by space flight missions.

- contribute to gain a deeper understanding of crew productivity and reliability, in socially risky situations and extreme environments.

Hence, people from several naturalistic space analogues and ground-based simulations have been surveyed with the aim to:

- compare the criticality of their extreme experiences with respect to the main latent and overt stressors yielded by future deep space flight exploratory missions.
- Quantify the general statement which claims that no place on Earth can reproduce the exact extreme space conditions (level of analogy).
- Identify the crew autonomy level (classification of the *Earth, machine, human* components).
- Assess the effects on individual well-being and team performance of the above mentioned stressors in order to uncover the critical criteria for the habitability of manned vehicles.
- Propose countermeasures for a successfull integration of the human factors subsystem in the early mission planning.

Methodology

System Vision

In order to meet the objectives of the previous paragraph, a systems engineering approach is followed (figure2). Given the high complexity and peculiarity of future human space missions, the coupling of engineering and human factors subsystems has to be considered since the beginning of the mission planning. This results in focusing on the role of *Earth, human and machine* components.

The first is the support given by the control centre all along the mission; the second concerns all the issues related to the presence of humans "on board" (physiological and psychological issues) and finally the machine component regards all the technological challenges needed for a successful mission. The object of our study is focusing on the human component i.e. the set of engineering knowledge that the crew needs along with training to assess the right countermeasures for the human factors issues. The investigation of behavioural effects of prolonged co-living and co-working in *analogue natural envirnoments* and *ground-based simulations* will lead to assess criteria and propose countermeasures for the habitability of spacecraft. Finally, the loop of the system engineering approach, hopefully closes with the habitability of the manned vehicle and the design of the spacecraft (out of the scope of the present paper).

Role of Relations of Human, Machine and Earth

With the aim to conquer Solar system, neither machine, no matter how perfect it might be, nor collective mind of the Earth or a mission control centre would be able to replace a human being in space [2]. The achievement of this objective is only possible by combining human, machine and the Earth as a basic element of the control loop and decision-making process [2]. Similar to any complex system, it is necessary to look for optimal combinations of relative "weights" of these elements within the system to ensure its maximum efficiency [2]. The main differences between Near Earth Orbit missions and interplanetary ones are [2]:

- communication between the crew and the Earth.
- The impact of space radiation on crew and on-board systems.
- Crew rescue in contingencies.
- Lack of resupply (complete resource autonomy).

For as successful implementation of an interplanetary human mission, the creation of integrated support (engineering, organizational, psychological) is needed [2]:

- *machine component*: concerning engineering and technological issues.
- *Human component*: crew; it should learn to treat contingencies as routine operations. Crew proficiency with respect to a specific utilization task is complemented by intuition based on experience and specialized knowledge; general engineering training as well as mental stability under stress is needed. Cosmonauts' creativity that is the ability to adequately analyse actions in case of a contingency and to find optimal recovery means is required.
- *Earth component*: ground control loop and on-board control loop define the mission control profile.

Latent and Overt Stressors

Over the course of a long duration mission, psychological issues tend to develop from two kinds of sources [3]:

- *Latent stressors*: such as the tedium of life aboard a shuttle, are unavoidable realities of space flight. Furthermore, these issues develop very slowly over time and can be very difficult for observers on the ground to detect and remedy.
- *Overt stressors*: arise from specific events: critical failures of equipment and family issues back on Earth are both examples of overt sources of tension. The effects of this type of stressors are easier to detect because of their sudden onset, prevention is often impossible. It is difficult to predict how individual crew members will react to different overt stressors events though the effects are often very similar to those produced by latent stressors and surely are equally dangerous to the health of a crew member and the success of the mission.

Latent stressors are often the most difficult to deal with because we usually detect them only from their "wake effects" [4]. Of course, once we detect the wake, the ship has passed, so prevention through good design is the order of the day [4].

Three main categories of stressors yielded by future space flight missions have been identified [5], [6], [7] and so classified:

- *Latent Stressors linked to emotional and interpersonal issues*:
  - monotony/routine;
  - boredom/tedium;
  - extended confinement (more than 6 months in a spacecraft size-like environment);
  - emotional isolation from the outside world and limited social contacts (impossibility to take part to family events or special celebrations);
  - absence of familiar comforts and separation from traditional social support;
  - cultural differences and potential incompatibilities of crew members from different countries (languages and values);
  - gender differences;
  - co-operation in small teams (less than 7 people);
  - high social density;
  - lack of privacy (people-place relationship);
  - unclear authority lines (leadership issues).
- *Latent stressors linked to the extreme conditions issues*:
  - communication time lag (greater than 20 minutes which is the average one way Mars communication delay);
  - low tolerance for errors
  - constant peril (continous exposure to hazardous environment i.e. weightlessness and radiation);
  - sleep loss;
  - lack of comfort;
  - impossibility of resupply (Mars mission scenario);
- *Overt Stressors*:
  - death/illness of crew member's relative or of a crew-member itself;
  - extra vehicular activities;
  - equipment malfunction.

Survey

Once the stressors classified, an *expo-facto* research has been realised [8]. The investigation is a non-experimental, descriptive study [9], using a single measurement in order to obtain the evaluation of the above mentioned stressors, on the basis of the participants extreme experience, and to make some reccomandations from the obtained results [9]. The study population consists of 17 participants who experienced *co-living and co-working* in the following extreme scenarios:

- Antarctic settings (6 subjects from Kerguelen and Concordia stations).
- Caves extended exploration (2 subjects).
- Remote sea-based oil drilling platforms (1 subject).
- Remote military outposts (1 subject).
- Drone pilots (6 subjects from ATV1 CC mission).
- Mars 520 (1 subject).

Every single participant has been asked, through a questionnaire, whether he experienced or not the above listed stressors and to attribute a severity (gravity) on a scale from zero (no severity) to five (maximum of severity) to it. Once the probability of occurence rated, for every stressor, the risk

that it may lead to the mission failure (feared event) has been evaluated through the formula $R = P \times G$ i.e. the risk is given by multiplying the probability and the gravity.
Finally, the criticality for each of the six scenarios considered is obtained by combining the risk and the number of stressors matched, normalized on a scale from zero to five. The criticality of each scenario belongs then to the domain $[0, 5] \times [0, 5]$.
In order to quantify the general statement which claims that no place on Earth can reproduce the exact extreme space conditions, each scenario has been compared to the most critical [10] one which therefore represents the reference scenario: *Mars mission with crew landing*. Hence, the distance from the reference scenario, whose coordinates in the mentioned domain are (5,5), and every scenario is computed. The bigger the distance the lower the level of analogy between the relative space analogue and the reference scenario.
For the present analysis, we have to keep in mind that the impact of the above stressors is strongly connected with the level of crew autonomy as well as the support that can be provided by the ground. That is why the survey participants also have been asked to rate their autonomy level during their extreme experience.
The arithmetic mean has been considered as representative value for the scenarios with more than one survey participant. The low dispersion level of the collected data justifies the approximation of replacing the mean value to any other one: this allows us comparing the obtained results on the same scale of accuracy with respect to the scenarios with a single survey participant.
Finally, the survey included open questions with the aim to assess the effects on individual well-being and team performance of latent and overt stressors. This also helped establish a link between the design of habitats and habitable structures for analogue extreme environments and habitability of manned vehicles.

Results

Stressors Analysis: Criticality of Scenarios

A measurement of the impact of latent and overt stressors on individual well-being and team performance that is the **criticality of scenarios** is obtained. This also measures the potential of psychological, interpersonal and environmental factors to lead to the mission failure (feared event).
The higher the criticality of scenario, the lower the margin between the effects of the afore-mentioned factors and the feared event (figures 3, 4, 5 and 6).
In figure 3 the criticality of scenarios is analysed regarding to the first category of latent stressors i.e. the ones related to emotional and interpersonal issues. The *x-axis* represents the number of stressors matched on a normalized scale from zero to five. The more the number of stressors matched the higher the criticality of scenarios. The *y-axis* represents the severity of the scenarios i.e. the risk of mission failure, rated on a scale from zero to five. The reference scenario has the highest criticality [10]. Hence it occupies the top right vertex of the considered domain i.e. its coordinates are (5,5). The

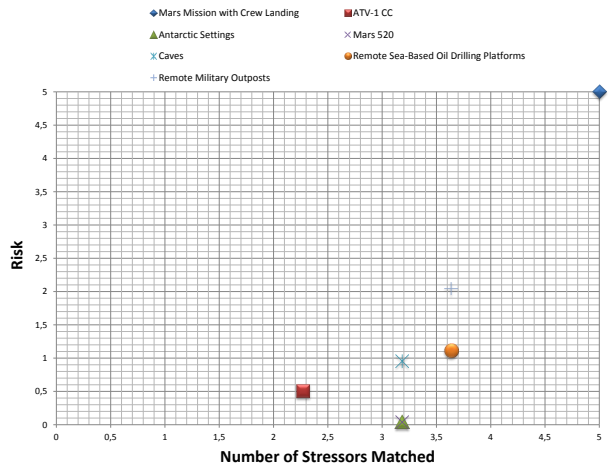

Figure 3: Latent Stressors (Emotional Issues) Analysis: Criticality of Scenarios

higher the risk, the higher the criticality of scenarios. As a direct consequence, the criticality is bounded in a square domain $[0, 5] \times [0, 5]$.
The *remote military outposts* and *remote sea-based oil drilling platforms* scenarios match the highest number of stressors. In the order they follow the *caves extended exploration, Antarctic settings and Mars 520* scenarios (same value of number of stressors matched) and finally the *drones piltos* scenario. On the other side, *remote military ouposts* scenario exhibts the highest risk value while *Antarctic settings* and *Mars 520* scenarios the lowest. By combining these results, a *cartography of the criticality of the scenarios* regarding the mentioned stressors is obtained.
The objective of the following two figures is tracking the evolution of the criticality map along with different categories of stressors. Regarding the second category of latent stressors

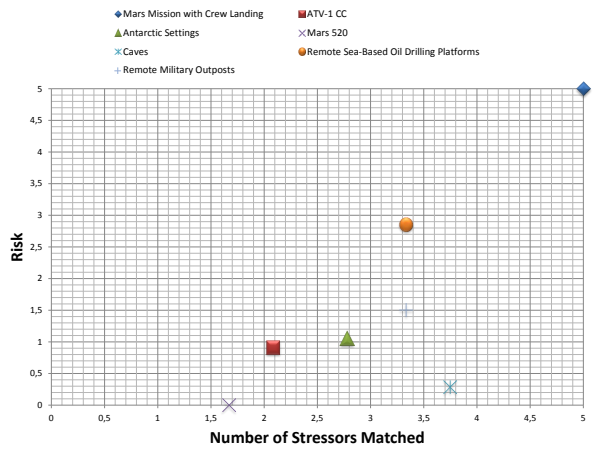

Figure 4: Latent Stressors (Extreme Environment Issues) Analysis: Criticality of Scenarios

i.e. the ones related to extreme environmental issues, the

remote sea-based oil drilling platforms scenario is the most critical among the survey scenarios while*Mars 520* scenario exhibits the lowest criticality. Figure 5 identifies the *Antarc-*

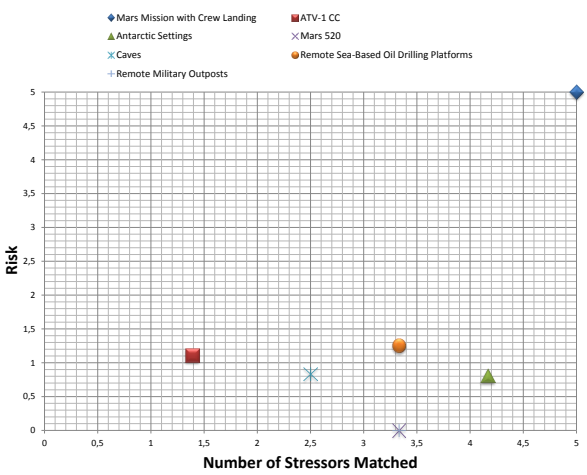

Figure 5: Overt Stressors Analysis: Criticality of Scenarios

tic settings scenario as the closest to the reference scenario in terms of stressors matched and the *remote sea-based oil drilling platforms* scenario as the most severe. Figure 6 takes

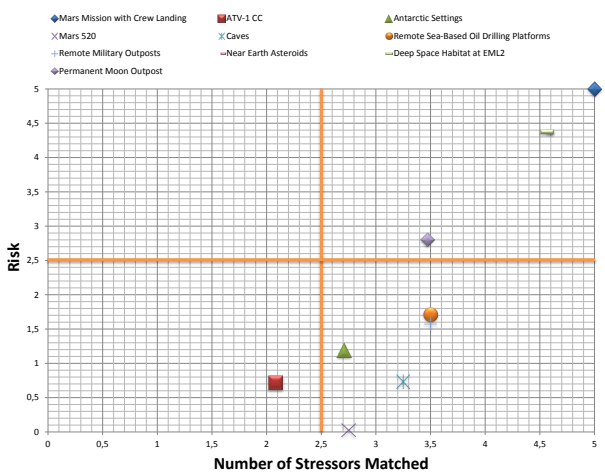

Figure 6: Global Analysis: Criticality of Scenarios

into account all the results of the previous three graphs, being a global cartography of the criticality of scenarios. The total number of latent and overt stressors is normilized on a scale form zero to five (*x-axis*). The domain has been divided in four squares to better visualize the most severe scenarios and the ones that match the highest number of stressors. The top right square gathers the future human deep space exploratory missions. The bottom right square includes the most critical space analogues scenarios (high number of stressors matched with severity lower than 2,5). Finally on the bottom left square tle less critical scenario.

Scenarios VS Future Human Space Missions: Level of Analogy

Table 1 represents the level of analogy of every single scenario with the reference one. The level of analogy is computed by using the classing formula of the distance of two points in a plane. The values of the level of analogy belong than to the domain [0, 7,071]. This same computation could be iterated with other reference scenarios. These results quantify the general statement which claims that no place on Earth can reproduce the exact extreme space conditions. The shorter

Scenarios	Level of Analogy
Near Earth Asteroids	0,761
Deep Space Habitat at EML2	0,761
Permanent Moon Outpost	2,671
Remote Sea-Based Oil Drilling Platforms	3,608
Remote Military Outposts	3,739
Antarctic Settings	4,448
Caves Extended Exploration	4,608
Drones pilots	5,179
Mars 520	5,46

Table 1: Level of Analogy

the distance the better the analogy.

Analysis of Scenarios: Crew Autonomy Level and Mission Duration Effects

Figure 7 represents the role of relations between *Earth, Human and Machine* component. The red segment in the bars represents the crew autonomy level. The reference scenario is the dream of modern cosmonauts [2]. Mission success is a function of increased role both of the human and machine components of the triad. Crew becomes practically autonomous, where well-being of a crew-member and mission scientific and technical success depend on entire crew proficiency. With time and experience, better working conditions may appear (better cohesion and solidarity of the group) on one side and less vigilance and caution on the other one. Duration of the mission increases the different risks of factors. Cumulated fatigue may become unsustainable. Duration also has a strong impact on group dynamics: hence problem solving appears to be an essential countermeasure to preserve social aspects. Preserving social component while working and living focused on short term goals, the major mission success goal has to be kept in mind.

Critical criteria for the habitability of manned vehicles

On the basis of individual well-being and team performance effects of latent and overt stressors, critical criteria for the habitability of manned vehicles are assessed. Our survey shows that a poor design and ugly spaces trigger negative reactions even to small adverse events. On the contrary a beautiful environment creates a peaceful state of being. Habitat

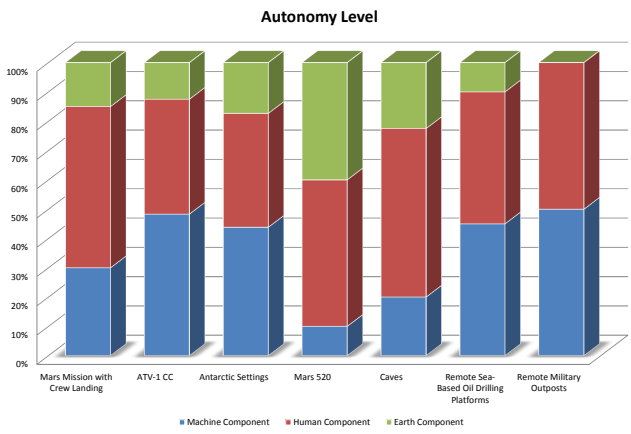

Figure 7: Crew Autonomy Level: Analysis of Scenarios

should include recreation facilities to counteract the effects of monotony and **fictitious places** so that the crew feels to run the daily activities as on Earth (e.g. office, dedicate place to eat, drink, sleep...). **Crew selection** in terms of individual personality is of paramount importance to favourite good social interactions which help survive a confined habitat. The survey revealed that the **presence of a private area**, even very small, for each crew member, where to stow personal items, record personal experience, have a rest, is the most critical issue. It helps create a sense of protection and allows to take a small break from the co-living and co-working. A **clear definition of space use** (with some possibilities for multipurpose use) helps to perceive the space bigger than it is.
Finally in order to counteract the effects of sensory deprivation (no natural light, absence of smells and body contact, permanent noise, orientation lost), the concept of *design with crew and ergonomists in the loop* results an essential need for the outcome of the mission.
Comfort (e.g. of sleeping equipment), nutrition and performant equipment are essential elements of the habitat and have a strong impact on overall crew well-being.

Stressors VS Countermeasures

On the basis of the survey participants' answers, some countermeasures are proposed for a successful integration of the human factors subsystem in the early mission planning.
With respect to the "*adaptation to extreme conditions*" category of stressors the following reccomandations are proposed:

- **specific crew training** in the management of nominal and crisis events: this helps develop interpersonal communication skills needed to reach a high level of mutual trust before the mission starts. Autonomy should be allowed in decision making with proper reporting to the mission control centre. Real time training during critical phases should be provided.

- An **in-depth knowledge of the system beahaviour and spaceship design** along with its fonctions and operations help understand, accept and control the associated risks.

- A strong **group behaviour** and commitment are essential to feel at home with your colleagues and mitigate isolation effects.

- **Clear organisation of responsabilities**. Roles and tasks should rotate along the mission duration so that each crew member has a global understanding of other crew members roles difficulties. Team-work should be preferred when possible.

- **Proper schedule**: Organise work and social activities within the same day, when possible.

- Provide the best quality food and water to get a fully **balanced diet**.

Regarding the "*emotional issues*" category of stressors, the following countermeasures are proposed:

- **organization of events and surprises**.

- **Continous dialog** among the crew members (leave open space for feedbacks and discuss about the problems arising during the co-living), sharing the challenge and avoiding developpement of single ego. Create a **sense of camaraderie** (sharing mistakes and successes and help each other) and a**sense of mission**: avoid create extra isolation.

- **Crew supervision by the ground** to avoid overloaded schedule. The ground should also provide support to crew families.

- **Pre-departure team-building and conflict solving training**.

- **Crew Selection**: couples should be selected for long duration missions. Crew members should be complementary and have similar hobbies to enjoy group social activities (eg. each crew member playing a different musical instrument). Crew should share at least one common language and be aware of cultural differences.

- Create a **sense of goal and achieving something** (eg. getting a master during the trip, writing a book...)

In case tragic events occur to crew families or friends, **psychological support** from the ground should be provided and every contact possible with someone close to the crew member should be established.
Regarding unforseen failures on critical equipments that can degrade the working and living environment very quickly, crew should rely on people who know how to fix the problem or specific protocols and procedures (no trial and error method).

Conclusions

Criticality of space analogue scenarios varies according to the stressors considered unlike *Mars mission with crew landing* scenario. This affects their level of analogy with future actual space missions.
When analysing the only space analogues, including survey participants from different scenarios i.e. polar settings or sub-sea simulations would result in a more complete cartography of criticality versus latent and overt stressors.
We also recommend to put in place all the efforts to centralize the space analogue extreme experiences with the aim to get a common feedback.
When comparing these scenarios to the reference one, we have to keep in mind that the accuracy of the cartography may be affected by some shifts in criticality due to the fact that the number of crew members or the concept of confinement etc. in space analogues do not match exactly with those of future space missions.
Moreover, the level of crew autonomy, the ground support and the mission duration also have a strong impact on the above mentioned accuracy.
Finally, our study showed that we cannot rely completely on space analogues to prepare future manned missions, given the relative small level of analogy. Intermediate destinations i.e. Near Earth Asteroids, Moon-Earth Lagrangian points are a step forward experience in terms of criticality regarding the space analogues and represent a safer approach to prepare future manned missions en route to Mars. Furthermore, intermediate destinations could be a relative short term Space Agencies objective with the result to increase the general public's imagination. New generations would be captivated by this incredible human challenge as already happened at the epoch of the Moon landing.

Regarding the habitability of manned vehicles the criteria to keep in mind are:

- **Crew is a central element of the habitat** and designing according to his needs i.e. private space, as much comfort as possible represents the first step to improve the co-living and co-working in a confined place.

- **Eye contact on an external space**: the more the windows, the more the "access" to an external space (although dark everywhere), the lesser the feeling of confinement.

- **Perception of the space**: use some artifices (e.g. mirrors, 3D screens...) to perceive to live in a bigger space than it really is.

- **Foster mental projections** thanks to the choice of interior decor, materials, colours, paintings, sense of verticality or horizontality and the power of imagination (encourage good social interactions, recreation activities i.e. playing music together). Travelling with the mind in a fictitious dimension allows forgetting for a while the conditions of confinement and isolation.

Common areas design should be neuter and functional and space organization considered as a priority. Private crew quarters should be built out of a *LEGO* concept with the possibility to adapt the personal habitat according to the change in feelings and emotions.
Finally the design of manned vehicles is a cyclic process (figure 8): crew needs satisfaction trough habitat arrangement and psychological illusion (i.e. feeling of living in a space bigger than it really is), good social interactions and recreational activities have a positive effect on overall well-being and emotions. This helps stimulate imagination. Imagination helps travel with the mind and ideally escape the crew confined condition. This is why all the necessary efforts to improve crew habitat have to be put in place. Habitability of manned vehicles not only concerns the issues

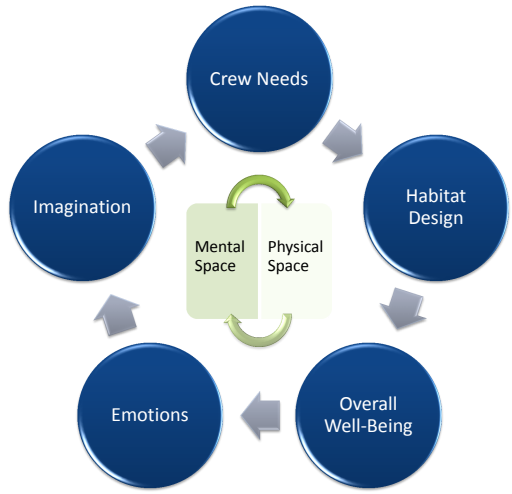

Figure 8: Habitability of manned vehicles: a cyclic process

related to the physical space i.e. provision of windows, private quarters etc. It is all about creating the necessary conditions to develop a mental space by including human factors in the design loop. Physical and mental spaces have reciprocal influences and their coupling is an asset for sustainable long duration missions in the deep space.

Further studies along this direction should be performed to finally be able to design the spacecraft by taking into account the mentioned criteria.
Besides, other relevant questions can be raised in relation to follow-up studies in other disciplines (e.g. automation of dependent people with reduced mobility) ending, hopefully with interesting spin-offs for terrestrial applications.

Acknowledgements

The authors warmly thank all the survey participants for their support in our investigation.

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