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Factors Impacting Habitable Volume Requirements:
Results from the 2011 Habitable Volume Workshop

April 18-21, 2011
Center for Advanced Space Studies-Universities Space Research Association
Houston, Texas

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Abstract

This report documents the results of the Habitable Volume Workshop held April 18–21, 2011, in Houston, TX, at the Center for Advanced Space Studies, Universities Space Research Association. The workshop was convened by NASA to examine the factors that feed into understanding minimum habitable volume requirements for long-duration space missions. While there have been confinement studies and analogs that have provided the basis for the guidance found in current habitability standards, determining the adequacy of the volume for future long-duration exploration missions is a more complicated endeavor. It was determined that an improved understanding of the relationship between behavioral and psychosocial stressors, available habitable and net habitable volume, and interior layouts was needed to judge the adequacy of long-duration habitat designs. The workshop brought together a multi-disciplinary group of experts from the medical and behavioral sciences, spaceflight, human habitability disciplines, and design professionals. These subject matter experts identified the most salient design-related stressors anticipated for a long-duration exploration mission. The selected stressors were based on scientific evidence, as well as personal experiences from spaceflight and analogs. They were organized into eight major categories: allocation of space; workspace; general and individual control of environment; sensory deprivation; social monotony; crew composition; physical and medical issues; and contingency readiness. Mitigation strategies for the identified stressors and their subsequent impact to habitat design were identified. Recommendations for future research to address the stressors and mitigating design impacts are presented.

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1. Introduction

The action. NASA is studying potential human missions beyond low-Earth orbit (LEO) to establish requirements for technology investment and system development. As part of the study process, assumptions are made for the mass and volume of the habitable systems required to support these missions. In 2010, the Human Exploration Framework Team (HEFT) led one of these studies. They gave an action to NASA's human health and performance (HHP) community to determine whether HEFT's assumed habitable volumes for the Deep Space Habitat (80 m^3) and the Crew Transfer Vehicle (CEV) (18 m^3) were sufficient to support the planned crew of 3 for a year.

The difficulty of answering this question, in particular for the Deep Space Habitat, is that to date, there are no universally accepted *a priori* criteria for judging adequate volume limits for the proposed design reference mission's parameters. While the NASA-STD-3001, Volume 2 (United States 2011) defines general functional volume requirements and the NASA/SP-2010-3407 Human Integration Design Handbook provides guidance for determining volume and the factors that must be considered, both are based on research and studies that do not directly correlate to determining *minimum* volume for *long-duration* (over 6 months) missions.

Historical habitats. There is some precedent for long-duration space missions that are potential sources of data. However, these precedents must be assessed to determine whether they are applicable to establishing minimum volume design requirements. For example, Skylab and the International Space Station (ISS) have served as long-duration spaceflight precedents, but since neither was volume constrained, are not good examples of minimum volume requirements.

Confinement studies. Another option to define minimum volumes is to use data from confinement studies. Several confinement studies commonly referenced for volume determination include Davenport et al. 1963; Fraser 1966; Fraser 1968; and Celentano et al. 1963 (the latter is the seminal reference upon which habitability requirements in NASA STD 3001 are based). These and other methods are described in detail in Simon 2010 and Cohen 2008. There are, however, several limitations concerning confinement studies:

1. Limited durations of testing. No experimental data exists for long-duration mission requirements exceeding 6 months, resulting in large extrapolations of habitable volume requirements for these durations (Simon 2010). This makes it difficult to assess whether the volumes reported in these studies will be accurate for missions on the order of the HEFT study (365 to 450 days).
2. Low fidelity. There are many habitability and behavioral factors such as psychosocial stressors that contribute to the perceived adequacy of a volume. These cannot be captured by simple low-fidelity confinement and bed rest studies.
3. Variable types of volumes. Definitions of the types of volumes (habitable, pressurized, net habitable, living) tend to vary across the studies. This makes it difficult to derive consistent volume requirements with confidence. (Cohen 2008; Simon 2010; NASA 2010; Szabo 2007)

Analogs. Another potential source for volume requirement data comes from both Earth-bound and in-space analogs. NASA's Human Integration Design Handbook (HIDH) provides volume requirements based upon undersea analogs somewhat applicable to shorter-duration spaceflight missions (United States 2010). The limitations of using ground-based analogs for long-duration volume requirements mainly stem from the differences between the gravity environments and the lack of extreme long-duration analog environments capable of simulating the level of autonomy and isolation experienced on missions to deep space. (For more information on the limitations of analogs for application to volume determination determinations see Rudisill et al. 2008 and NASA 2010.)

While developing volume requirements based on evidence from analogs may be adequate for shorter-duration missions (less than 6 months), determining the adequacy of the volume for long-duration missions is a much more complicated endeavor. The volume required for any duration is a function of multiple factors that contribute to the adequacy of a volume, such as how the interior is laid out and how spacious an interior is perceived. When designing for longer-duration human missions beyond LEO, however, the cumulative impact of stressors on the crew become increasingly important.

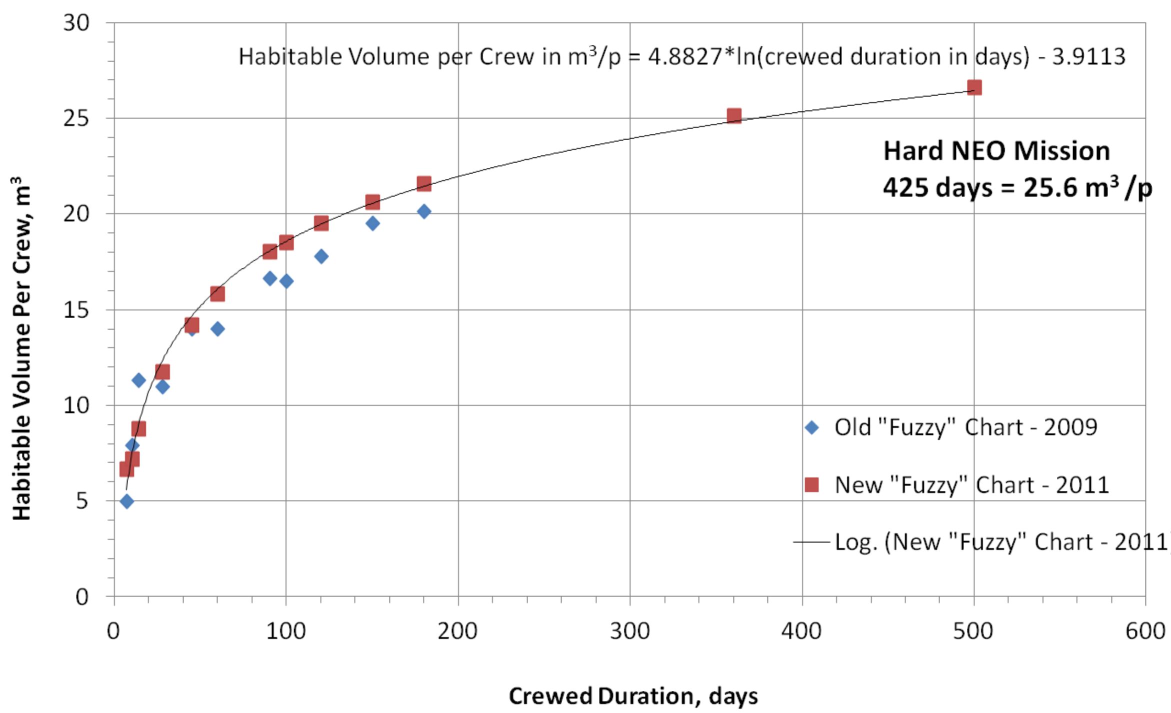

Figure 1: Averaged habitable volume curve.

Path forward. These considerations led the HHP group to determine that definitively answering the HEFT's volume question with a specific number is not possible at this time. The general consensus was that the assumed volume was too small, but there isn't enough data to determine what the 'right' number is. Therefore, the recommendation to the HEFT was to continue to use the data[1] provided in previous studies in the interim (Figure 1) while additional targeted research is done to develop an improved understanding of the stressors and mitigating design features (Unpublished data, Simon 2011).

In addition, a workshop was proposed to bring together experts from a broad spectrum of disciplines to identify these stressors and features. This workshop was held April 19-21, 2011, at the Universities Space Research Association facility in Houston, TX. The purpose of this report is to document that workshop and how the findings may be applied toward identifying areas for future research to be added to current research planning.

2. Workshop Description

In preparation for the workshop, a planning group was assembled of subject matter experts with experience in habitat design, human factors, and behavioral health and performance (included in Appendix B). This group met to determine the specific goal, objectives, participants and agenda for the workshop.

2.1 Goal and Objectives

The goal of the workshop was:

> *"To develop a response to the NASA Human Exploration Framework Team on how to address the 'habitable' and 'net habitable' volume necessary for long-duration human spaceflight missions by identifying both the design issues as well as the psychological issues that will impact the human. The product goal is the development of a standard(s) and associated information ready to publish in the Agency's NASA STD 3001: Space Flight Human System Standards, Volume 2 – Human Factors, Habitability & Environmental Health and the Human Integration Design Handbook."* Workshop Planning Documentation.

Life in confined isolation is an existence within a non-enriching environment that is potentially physically and cognitively depleting. Confinement stress continues to build as coping mechanisms deteriorate and neurobiological and neurostructual changes occur. The workshop planning group noted that some studies suggest that the volume and/or layout of the space could mitigate these stressors, but that lack of isolated confinement testing beyond 6 months limited the amount of applicable information to make a numerical decision. Therefore, workshop planners determined that rather than trying to define "a number" in the short time available for the workshop, the workshop top-level objectives would advance the knowledge of the community of practice toward determining those factors that influence volume and habitat design considerations. These top level objectives were to:

[1] Data compiled from: Celentano 1963, Optimal; Davenport, Congdon, and Pierce 1963, (average of 3 crew and 5 crew); Sherwood and Capps 1990, (multiplied by 0.6 for habitable volume); Guidelines and Capabilities for Designing Human Missions (2003), NASA TM-2003-210785, p. 47; and Human Integration Design Handbook 2010, undersea analog curve, p. 563.

- Identify the psychological/behavioral health factors that impact long-duration missions (both spaceflight and analog) and how those factors contribute to habitat volume, interior layout acceptability, and specifications
- Identify potential countermeasures to these psychological design factors and their subsequent impact to habitat specifications
- Develop the list of parameters that can be used to adequately define how volume should be established such that psychological stressors are minimized
- Provide advisories about the human factors consequences of not conforming to these metrics
- Identify critical knowledge gaps to inform future research efforts to either characterize the stressors themselves, quantify their impacts, and/or identify potential stressor mitigation techniques and measure their effectiveness
- Identify the work necessary to arrive at useful design driving recommendations or requirements including numerical values for volume requirements.

2.2 Participants

To achieve these objectives, workshop participants were desired who:

- Had training in anthropology, neurology, psychology, human factors, medicine, naval ship building, interior design, and physiology, and/or
- Had experienced extreme isolation or long-duration confinement, thus had experience in space or terrestrial analogs
- Had contributed to specific research addressing habitable volume, psychological stressors, or habitability factors captured in existing reference literature
- Have been identified as leading subject matter experts in their respective fields of study

To capture the broadest set of expertise, invited participants included NASA civil servants, contractors, academia, the military, and other researchers from outside NASA. A full list of the participants who attended may be found in Appendix B.

2.3 Agenda

The workshop agenda (Appendix C) spanned 4 days and included both plenary and breakout sessions. The workshop started with a plenary session that provided background material on habitable volume determination for the CEV and the current NASA human exploration missions and design efforts. Characteristics of these future missions were based on the assumptions of a design reference mission that included the following assumptions:

- Mission duration of 12 to 15 months
- Travel to a near-Earth asteroid
- Three to four crewmembers

The second day of the workshop began with a crew forum featuring NASA astronauts with long-duration experience in Earth orbit, Antarctic analogs, and submarines. This crew forum provided valuable insight and the unique perspective of personal experience of long-duration human spaceflight challenges.

Each workshop participant then provided a short background of their experience and contributing knowledge to the discussion. Following this, the participants were split into two groups. Group one (Behavioral Health and Performance Team [BHPT]) included psychological/behavioral health experts who identified and refined a list of psychological stressors. Group two, (Tasks and Functions Team [TFT]) included predominantly human factors and habitat design experts to identify the functions and tasks, as well as the layout implications of the stressors identified by group one. Workshop planners were distributed between the two groups to provide top-level guidance and push for desired products.

Several separate and combined sessions of these groups were carried out over the second and third days to integrate and communicate findings of each to achieve the workshop objectives. The participants identified the most salient design-related stressors anticipated for a long-duration exploration mission. The selected stressors were based on scientific evidence, as well as personal experiences from spaceflight and analogs. They were organized into eight major categories: allocation of space; workspace; general and individual control of environment; sensory deprivation; social monotony; crew composition; physical and medical issues; and contingency readiness. Mitigation strategies for the identified stressors and their subsequent impact to habitat design were identified. On the last day, a final debrief of the findings was presented to and discussed by the participants. To facilitate continued collaboration and completion of the products after the workshop, a "community of practice" was created from this group of participants.

3. Workshop Products

The following products were planned for the workshop:

a) A list of the major psychological stressors associated with long-duration habitation or extreme isolation and confinement environments (Table 2)
b) A matrix of those psychological stressors impacting habitat design that captures definitions of the stressors, potential mitigation strategies, necessary research, and potential analog candidates for testing (Appendix D)
c) A recommended research plan to further inform current human integrated research plans and analog testing organizations (summarized in Table 3)
d) A publication to document the findings of the workshop (this report)
e) An addendum to the existing habitat design standards detailing the impact of these psychological stressors on habitat design

The goal of these products was to capture knowledge from the workshop for consideration in updating NASA's best practices, and to provide clear recommendations to stakeholders for a needs-driven research plan that will benefit future human spaceflight. Products a, b, c, and d were completed during the workshop, or in follow-up activities involving the community of practice established by the participants. Once additional research is completed from these recommendations, an addendum to the NASA standards (Product e) will be prepared for submission. In the interim, design and layout recommendations (Table 3) have been provided to the HEFT. The following sections describe these products and recommendations in detail.

3.1 Psychological Stressors Identification

The purpose of the behavioral health breakout session was to characterize, based on the scientific and anecdotal evidence, the behavioral health and performance stressors inherent to a future long-duration mission. This discussion was achieved by asking the participants to consider the top stressors associated with such missions. Each participant then listed what they considered the top three stressors.

The list of stressors generated by the BHPT was assessed, and recurring themes were identified. The mapping of the stressors to these categories is shown in Table 1. Each of the stressors in "bold" text was addressed in a matrix developed after the workshop to inform future habitat design efforts and habitable volume studies.

Some stressors were identified as those that could be mitigated via non-habitability related countermeasures, for example "align expectations with reality" and "schedule presleep period." These were noted then set aside since the goal of the workshop was to identify stressors that impact habitable volume or design.

Stressors that were identified as being related to habitability, habitat design, and interior volume or layout were then divided into one of the following eight emergent categories:

1. Allocation of space
2. Workspace
3. General and individual control over the environment
4. Sensory deprivation and monotony
5. Social monotony
6. Crew composition
7. Physiological and medical issues
8. Contingency readiness

The purpose of the remaining sessions was to bring together the BHPT and the TFT, to discuss how habitat requirements (including volume) can mitigate behavioral health and performance risks. The following section describes the outcome of these discussions and the follow-on work contributed by the workshop community of practice.

Table 1 Mapping of Psychological Stressors to Categories

Allocation of Space	Workspace	General and Individual Control over Environment	Sensory Monotony	Social Monotony	Crew Composition	Physiological and Medical	Contingency Readiness
Feeling of crowdedness	Workload boredom	**Lack of accommodation/ customization for cultural differences or personal preferences**	Under-stimulation	Separation from family and friends	Recruitment and Selection	Radiation	Lack of duplicate vehicles
Lack of privacy	**Meaningless work**	**Lack of individual control over the environment**	Poor aesthetic design	Isolation	**Composition**	Nutrition	**Event (something external that requires contingency planning)**
Confinement	Faulty equipment		Physical monotony (muscular, tactile, etc)	Separation from family routine	Training	CO_2	Safety
Involved logistics management and lack of or inefficient storage	Faulty procedures		**Lack of sensory stimulation**	**Limited communication**		Sleep disruption	
Lack of personal space	**Faulty Design or Layout**		**Sensory deprivation**	Family problems		Medical procedures	
Separation from home (physical)			Lack of food freshness and variety	**Social deprivation**		**Hygiene separation**	
				Emotional connections with mixed gender			

3.2 Psychological Stressors Impacting Habitat Design

The workshop participants postulated that the likelihood of deleterious outcomes, such as health and performance decrements, could increase or decrease based on how these stressors are addressed in the design of future spaceflight habitats. Habitability requirements could therefore serve as mitigation strategies for these stressors and support human health and performance on a future long-duration mission.

Following the workshop, a matrix (Appendix D) was developed that outlined the eight categories and their associated stressors. A core team at NASA began populating the matrix based on discussions from the workshop. The matrix was then made available online, where the workshop community of practice was invited to provide additional inputs. Over a period of several weeks, this core team and the workshop community of practice refined the categories, identified gaps that need to be addressed via research and/or technology development, and provided additional recommendations to mitigate the stressors. Proposed research tasks to inform future habitat design efforts and habitable volume studies were then added to the matrix. Specific platforms, including analog environments such as Antarctica, were also discussed as potential venues for addressing research questions. Table 2 contains a summary of the descriptions identified in the refined matrix, which can be found in Appendix D.

Table 2 Stressor Descriptions

Psychological Stressor	Description
Allocation of space	**This category deals with the allocation and positioning of certain types of volume to meet psychological needs of the crew.**
Lack of Personal Space / Lack of Private Space	Private and personal space were both identified as highly important to the psychological well-being of crew, providing a retreat from social stressors, separation from work areas, a place to interact with family members, and providing a location for personal items and pastimes.
Feeling of "Crowdedness"	The perceived volume is adversely affected by the increased number of crew "traffic interactions" (which can include the displacement of one crewmember to allow for translation of others, or desired simultaneous use of equipment and workstations). Leads to a feeling of inadequacy of the size or layout of the habitat. This stressor can be mitigated by either implementing layout changes or adjusting schedule to reduce forced crew interaction/displacement.
Lack of Privacy of Waste & Hygiene Compartment	Increased privacy of highly personal activities such as crew waste collection and hygiene, contributes to a decrease in intra-crew conflict that could lead to decreased performance.
Workspace	**This category addresses the space allocated and workstations designed for meaningful work and activities needed for the psychological health of the crew.**
Lack of Meaningful Work/Activity	A lack of meaningful or motivating work/activity during a long-duration mission can lead to work apathy and disinterest, boredom, frustration, personal doubt and loss of focus, resulting in psychological and psychosocial stress and performance decrements.
Sense of Poorly Placed Stowage	Poorly placed stowage for performance of tasks can contribute to frustration or other forms of psychological stress
General and individual control of environment	**Control over lighting, airflow, temperature, etc.**
Lack of Individual Controls Over Temperature, Ventilation, or Lighting	Particularly in crew quarters, anecdotes indicated that insufficient levels of control over personal environment, particularly during sleep, can lead to poor sleep and the associated psychological stressors.
Lack of Reconfigurability for Cultural Difference / Personal Space Preferences	Customize-ability and reconfiguration to best suit needs of the crew can significantly decrease frustration at inflexible spaces. In addition, the ability to reconfigure and customize the environment and space adds the perception of choice and individual control, important personal concepts that are often lacking in isolation and confinement.

Psychological Stressor	Description
Sensory deprivation and monotony	**Space and resources should be provided to stimulate cognitive, visual, auditory, tactile, gustatory, olfactory, motor, etc.**
Lack of Stimulation/Sensory Variability	Current missions to the ISS provide a window with a close view of Earth, real-time communication with loved ones at home, and crew care packages that bring novel items with high sensory impact (i.e., fresh fruit) to astronauts throughout the duration of their 6-month stay. Future long-duration missions will not have these countermeasures as a way to mitigate sensory deprivation. Evidence shows that cognitive, visual, auditory, tactile, gustatory, olfactory, motor monotony, as experienced in isolated, confined, and extreme environments, can serve as a chronic stressor to the individual. Also, long-term lack of choice and control over work format and leisure can negatively impact mood – this impacts on volume as choice and control necessitate a minimum amount of variety.
Social monotony	**Resources and new technologies should be provided to facilitate communication with family and friends back home, to mitigate the monotony of being with the same small set of people for an extended duration of time, in a confined space.**
Social Deprivation / Lack of Common Areas	Lack of group spaces to encourage group activities can result in decreased crew cohesion.
Limited Communication with Home	Communication system with family and friends at home that offers confidence and privacy, providing a mechanism for the dissolution of frustrations, concerns, fear and anger, which in turn is essential for minimizing interpersonal conflicts.
Crew composition	**Number, gender, cultural differences, roles, leadership, relationship, crew selection and training.**
Crew composition may be a cross-cutting /high-level driver/ overarching category that impacts several other stressors in other categories, and can be addressed via other habitat requirements. Input and suggestions are welcome here.	1) Crew number can impact crew dynamics (e.g., potentially higher risk of marginalization and group dysfunction with 3 crew versus 4 or more). 2) The presence of female crewmembers among predominantly male crews can have a positive influence on group dynamics – mixed crews may impact design and layout (evidence on female vs. male preferences regarding environment and need for hygiene privacy). 3) Crewmembers of differing nationalities and cultures will have different expectations and needs regarding private space, leisure etc.
Physiological and medical issues	**Includes waste management.**
Lack of Hygiene Separation	Separation of dirty-clean areas has a psychological component beyond the functional requirement separating these areas. Other issues largely mitigated through space allocation and other venues.
Contingency readiness	**Planning to resolve emergency situations related to habitability and other equipment/resources.**
Lack of "Backup Plan" / "Rescue Scenario"	Long-duration isolation in extreme environments places severe stress on individuals that is magnified by the perception that certain contingencies have been overlooked. This "no escape" perception can be alleviated by providing backup contingencies for every scenario, including loss of a module.

Sections 3.2.1 through 3.2.8 describe each of the categories in greater detail, and provide examples of evidence that supports the most discussed factors as 'stressors'. Mitigation strategies that were discussed by the workshop community of practice are provided, along with recommendations for future research and/or technology development. These recommendations are not exhaustive; additional research may need to be conducted,

particularly once behavioral health and performance of individuals and teams in conditions of isolation and confinement for over a year, is more fully understood.

3.2.1 Allocation of Space

Stressors

The workshop community of practice identified lack of *personal space*, *lack of private space*, *lack of privacy for highly personal activities*, and *feeling of crowdedness* as top priority stressors for long-duration exploration missions. These related stressors were then categorized as "allocation of space." *Allocation of space* refers to the way in which the volume is used. As discussed by the workshop community of practice, a larger volume may be perceived as crowded if the layout and design of that volume is not optimally implemented. For example, positioning individual crew quarters adjacent to one another, versus separate from one another, may enhance a sense of crowdedness for some individuals. Additionally, specific requirements related to personal quarters and common areas need to be developed. Several of these stressors are discussed further below.

Personal space. Anecdotal evidence from studies of isolated and confined environments indicate that each person needs to have a place where they can be alone (Suedfeld and Steel, 2000). Before the addition of the temporary sleep station or dedicated U.S. Crew Quarters, lack of a private crew quarters for every individual was the biggest habitability impact reported on the ISS. Carrere et al. (1991, as cited by Suedfeld, 2000) conducted an observational study of use of space in small Antarctic stations and found that 60% of people's waking time was spent away from others. As noted by Stuster (1996), a rotational use of sleep chambers – referred to as "hot bunking" – is often despised for its lack of privacy and personal space (Stuster, 1996). Evidence from Antarctica further demonstrates that one's access to a personal area takes on added significance under conditions of isolation and confinement (Stuster, 1996; Salam 2011 and an unpublished NASA white paper by Otto, 2006). Stuster (1996) notes that "Antarctic experts recommend that provisions should be made to permit isolated and confined personnel opportunities to get away from their fellow crewmembers" (p. 224). Personal crew quarters in which a crewmember can be alone become extremely important on long-duration missions (Santy, 1983; Kanas and Manzey, 2008, as cited in Slack et al., 2008). A recent review of spaceflight crew comments debrief summary confirmed the crew opinion that individual, private quarters are particularly important on long-duration missions (NASA 2011).

Perceived crowdedness and privacy. The perceived crowdedness of the habitat may be a chronic stressor that also impacts crew health on a future mission. Paulus (1972) demonstrated that increasing the number of people in a housing unit (and hence the potential number of interactions between those people) leads to increases in levels of stress, while decreasing the amount of physical space did not. Higher social density is a major variable leading to major affective reactions and to increases in levels of stress, in relation to decreasing the amount of physical space. This was mostly seen with dorm inmates. Single cell inmates had a lower negative effect, which could be explained by the perceived sense of privacy provided by the single cells. There was a breakdown of square footage area ranging from 30.7 to 84.3 square feet per person. Hence, the social component of crowding appears to be a more relevant factor (Paulas, 1972). Perceived crowdedness of volume may be adversely affected by the increased number of crew "traffic interactions" (which can include the displacement of one crewmember to allow for translation of others, or desired simultaneous use of equipment and workstations). In his assessment of individuals living in analog environments, Stuster (1996) notes that designers should "ensure privacy of personal communications… (electronically as well as) from private quarters" (p. 211). In other words, to minimize perceived crowdedness, there needs to be auditory as well as visual and physical isolation.

Common areas. While the need for personal space was emphasized during the workshop, a common area that can accommodate all crewmembers simultaneously was also deemed necessary for a long-duration exploration mission. The lack of such an area was not specifically identified as a stressor, but it was acknowledged that the ability to facilitate all crewmembers in the same room was a critical aspect of supporting team cohesion. Stuster (2010) found that following Earth viewing, "watching movies" was the most preferred form of recreation of ISS crews. Hence, a common area should provide the means for all crewmembers to watch movies together. A common area that can accommodate recreational activities could also be made available to accommodate dining together. Anecdotal evidence suggests that taking time to dine together as a crew can significantly contribute to team unity.

A separate common area should be available to accommodate completing work objectives, given evidence that indicates teams with "project rooms" have clear advantages: increased learning, motivation, and coordination (Covi, Olson, Rocco, Miller & Allie, 1998). The separation of recreation and dining areas from work and hygiene areas is considered a critical component of habitat design for future long-duration missions.

Mitigations

Regardless of the volume number, steps need to be taken to ensure that the habitat includes personal quarters, minimizes the perception of social crowdedness, optimizes privacy, and also provides common areas. Inadequately designing the space can lead to a sense of perceived crowdedness and increased stress.

Based on evidence to date from previous spaceflight and analog missions, several recommendations that do not warrant additional research, were discussed. These proposed mitigations for optimally allocating space in the crew vehicle are:

- Provide individual and separate sleeping/personal quarters with visual and auditory isolation for each crewmember. The auditory and visual isolation enhance the sense of privacy. Personal quarters will help to mitigate sleep difficulties and mental fatigue, as well as provide a sense of psychological safety, and provide opportunities for reading, reflection and other restful activities.
- Provide a common area for work related objectives. Given that crewmembers will spend long periods of time at their work stations, however, and that a need for solitude may

arise, there should be an option for a visual separation between workstations to allow for the perception of increased privacy.

- Provide a common area that can duplicate as a "dining room" and "living room" if needed.
- Develop a habitat that does not rely on crewmember shifts. There was some discussion on the feasibility of rotation shifts on orbit versus keeping all crewmembers on the same schedule. Scheduling crewmembers in specific areas throughout the day may minimize the perception of crowdedness, enhancing well-being and mitigating stress. It was determined however that the costs of rotations (i.e., circadian misalignment and fragmenting the crew into splinters) is likely not worth this benefit.

Many of these recommendations concur with those found in NASA Standard-3001 (United States 2011) and the HIDH (United States 2010).

Recommendations for Future Research and/or Technology Development

The above recommendations are based on evidence to date. For additional requirements to be provided; however, additional research investigations and/or technology development is needed to address the following gaps. Below is a proposed list of research and technology activities that could yield habitability recommendations for mitigating some of the stressors related to allocation of space.

- Conduct research in long-duration, high-fidelity mock-ups to identify the optimal volume for personal quarters. Stuster (1995) proposes a minimum space of 84 cubic feet (3 feet by 4 feet by 7 feet), based on task analyses of activities conducted in personal quarters (sleeping, changing clothes, quiet leisure activities). Additionally, anecdotal reports from ISS indicate that the current crew quarters are of adequate size. As discussed by Otto (2010), however, this current perception may be relative to the fact that the entire vehicle has ample volume (and other factors, such as closeness to home). Whether this perception of adequate optimal volume for personal quarters remains, given the extended duration of future missions and the small volume of the overall habitat, is unknown. The volume of personal crew quarters in relation to total vehicle volume and mission duration is unknown and should therefore be systematically evaluated in both laboratory studies (if possible) and/or analog studies. Additionally, microgravity allows for more optimal use of the small volume relative to gravity constrained crew quarters; for instance, the crew can sleep strapped to the wall and does not require both horizontal space for sleeping and vertical space for dressing, etc. A partial gravity environment may not lend itself to these options that are available on the ISS.
- Identify volume adequacy for a long-duration exploration mission that will require testing of personal crew quarters in habitats with volumes that are smaller than currently found on the ISS, and for missions lasting 1 to 3 years. McMurdo and Concordia Station, which offer remote, long-duration missions in sensory deprived environments, may serve as potential analogs for evaluating this concept to some extent. Both of these Antarctic stations however consist of ample volume in comparison

to a future spaceflight habitat; additionally, while Antarctica stations offer a platform for evaluating stressors and countermeasures in conditions of long-duration isolation and confinement, there are key factors that are not analogous to spaceflight (e.g., crew size, access to the outside and minimal selection criteria of participants). Hence, a mission scenario with astronaut-like participants using a mock-up habitat in a remote and isolated environment such as Antarctica would be needed to accurately assess whether currently accepted volume in space is a by-product of the shorter-duration mission and the larger overall vehicle.

- Conduct research to determine which habitat designs and layouts are optimal for supporting behavioral and psychosocial health and performance outcomes. For example, some workshop participants believed personal crew quarters should be distributed in various locations throughout the vehicle to enhance the perception of the distance between the crew; others argued there were downsides to such a solution, since distributing personal space around common spaces would yield an increase in noise levels. Other options for distributing space exist. Investigations in a simulated spaceflight habitat where living quarters can be reconfigured will allow for evaluating optimal layouts. It is critical that these investigations occur over long-duration missions of 10 to 12 months, or longer, to capture factors that are dynamic over time, such as group processes (Suedfeld and Steel, 2000).
- Perform task analyses to identify dependencies between workstations, designing collocation of multiple workstations where crew must interact to perform a task, and separating workspaces that may interfere with one another. Ensuring optimal layout of work areas supports team cooperation and coordination.
- Develop and test scheduling tools that incorporate layout considerations, so that the distribution of crewmembers throughout the vehicle can be considered in conjunction with daily work rest schedules. Testing the usefulness and acceptability of these types of tools does not require a long-duration, remote environment, but rather a high-fidelity mock-up of a future habitat, or potentially, the current space station, where it is known that in areas such as Node 3, scheduling of operations becomes important to being able to use the allocated space.

3.2.2 Workspace

Work-related stressors identified by the working group participants included *lack of meaningful work/activity* and *sense of poorly placed stowage*. The category of "workspace" therefore is specific to the habitat-related aspects of work. For many individuals, work is a salient part of life; astronauts, who are high-achieving individuals, are inherently mission-focused and work-oriented. The content of work therefore is highly relevant to crewmembers on long-duration missions, particularly in the spaceflight exploration mission environment, where the purpose of the mission is to fulfill work-related objectives. Stowage issues have been present from Skylab to ISS. Not only is it a safety risk (Musgrave et al., 2009), but is also poses stressors on the crew who must deal with the excess equipment and trash that encroach on the living space, further reducing the habitable volume. It is postulated that this 'unnecessary work' contributes to a sense that the volume isn't large enough.

Stressors

Stuster (2010) found in his content analysis of eleven ISS astronauts' journals during their long-duration mission on the ISS, "work" was the most frequently discussed item in the journals; expressions of frustration concerning work and reactions to tedious and repetitive tasks compose the third most-frequently assigned subcategory. The emphasis on work will become all the more salient when crews embark on long-duration exploration missions, far from Earth. Evidence indicates that a lack of meaningful work or activity during a long-duration mission can lead to increased frustration (Stuster, 1996; Manzey, 2004; Palinkas, 2007; Stuster, 2010; Salam 2011). In fact, work related stress has been shown to contribute to deleterious outcomes including poor sleep, greater fatigue, and/or increased errors (Arkested et al., 2002; Linton, 2004; Jansson and Linton, 2006; Knudsen, Ducharme, and Roman, 2007), depression (Tennant, 2001), diabetes (Agardh, 2002), and cardiovascular disease (Kang et al., 2004; Bosma et al., 1998).

Mitigations

Karasek's demand-control model of occupational stress defines job stress as a function of perceived autonomy over one's job and perceived demands of one's job. Evidence shows that high demand jobs with a low level of autonomy lead to job dissatisfaction. Allowing the individual therefore to participate in defining the work over the duration of the mission can provide a sense of increased autonomy and alleviate stress. The habitat therefore should support, for each crewmember, the completion of "meaningful work," or work that personally engages the individual. As noted by one workshop participant who had previously wintered over in Antarctica, "meaningful work" could also be referred to as motivating work, given that none of the work done in long-duration missions is actually meaningless, but rather some aspects or types of work are more motivating and fruitful than others and thus more important for maintaining focus and interest.

Recommendations for implementing support systems and space for conducting work include:

- For long-duration missions, ensure that the mission design includes a role for meaningful work throughout the mission duration, not just at the destination. Skylab for instance included both human health and physiology experiments as well as unique solar observations that could only be accomplished in space, including the numerous engineering and technology objectives.
- Consider electronic resources to minimize volume requirements (e.g., files on a handheld device in place of printed manuals).
- Identify individual goals and plans for supporting autonomous operations. Crewmembers may wish to focus on creative science, rather than train on a check-list. Provisions should be made for scientific endeavors and to allow for shared authorship of a publication. Space and resources are needed to accommodate each individual's work and activities (e.g., science and laboratory equipment, electronic curriculum). Each individual should have their own workspace and materials should be appropriately placed for ease of use and improved functionality.

- Provide opportunities for self-paced study during long-duration remote missions, potentially related to science and engineering disciplines associated with the mission objectives.
- Fully assess stowage needs early in the design process to ensure adequate stowage for the mission length envisioned.

<u>Recommendations for Future Research and/or Technology Development</u>

Below is a proposed list of research and technology activities that could yield habitability recommendations for mitigating some of the stressors related to inadequate workspace.

- Evaluate individuals analogous to astronauts in high-fidelity environments to characterize the relationship between health and performance outcomes, and individualized goals/work opportunities.
- Conduct a task analysis to define a list of activities that will be performed on long-duration missions to inform designers of necessary equipment, procedures, task design and scheduling requirements. This more detailed concept of operations should be defined with key players (crewmembers, mission planners, vehicle designers, and Space Human Factors Engineering and Behavioral and Health Performance practitioners) and may yield insight into technology gaps for equipment that could minimize resource requirements.
- Determine protocols (including tools and metrics to assess) for identifying individualized goals for each crewmember to ensure meaningful activities. This research can include evaluations using the expertise of current astronauts and mission planners and trainers. Additional assessments with those in long-duration analogs (e.g., Antarctica) are also recommended.
- Evaluate current NASA processes for providing crewmembers with hardware and electronic resources and define how these are ensured to fit within specific parameters.
- Leverage ISS experience with stowage and consider placement for function and performance early in designs. Such an effort could be conducted on the ISS to identify optimal ways through which to use the space volume so that stowage and maintenance (as needed) facilitate, or at least don't prohibit, task performance.
- Collect and analysis data in high-fidelity mock-ups or spaceflight analog to identify the use of various work areas by time and number of crew to identify dependencies and interference between workstations and to optimize the size, layout, and configuration of workspaces.

3.2.3 General and Individual Control of Environment

<u>Stressors</u>

The Working Group identified *lack of individual controls over temperature, ventilation or lighting*, and *lack of reconfigurability for cultural difference / personal space preferences* as stressors for long-duration exploration missions. These stressors were then categorized as "General and Individual Control of Environment." Future space habitats will serve as the crew's living quarters for extended mission durations. Ensuring fundamental characteristics of the habitat (such as lighting, noise and temperature), are functional and adaptable, will be important to maintaining the behavioral health of the crew. Additionally, the ability to change the aesthetics of the habitat and even reconfigure layout aspects will help to optimize the livability of the habitat over long duration.

A mismatch between the demands placed on workers and the control they have over the physical environment in which they meet those demands is by definition stress-generating (Vischer, 2007). Evidence is accumulating that the physical environment in which people work affects both job performance and job satisfaction (Brill, Margulis, & Konar, 1985; Clements-Croome, 2000; Davis, 1984; as cited by Vischer, 2007). Other studies have found that that more personal control over the physical workspace leads to higher perceived group cohesiveness and job satisfaction (Lee and Brand, 2005).

Likewise, a lack of environmental control can lead to adverse outcomes. Preliminary analysis of sleep data by L. Barger and C. Czeisler related to sleep on the Shuttle and ISS indicates that for some crewmembers, hot temperatures and lack of air flow led to sleep disturbances. A NASA sleep quality questionnaire also found that inadequate light shades predicted the inability for some crewmembers to fall asleep on Shuttle. In 2009, proposed minimum lighting requirements for the Orion vehicle could have led to lighting levels that would have suppressed melatonin, and hence sleep onset, for some individuals. It is therefore important to ensure that standards and requirements related to minimum and maximum lighting and acoustic levels are defined based on the best scientific evidence, and are implemented correctly.

Adequate lighting is necessary for visual acuity, task performance and behavioral health. Evidence indicates, however, that lighting on the ISS is dim, as crewmembers are daily using portable light sources to complete work. Lack of local control of lighting sometimes interfered with scheduled activities on Skylab (Johnston, 1975, as cited in Stuster, 1996). In addition to supporting task performance, lighting of the proper intensity and spectral quality serves as the most potent stimulus for maintaining circadian rhythms, or the body's biological clock, to help facilitate sleep at night, and alertness during the day (Brainard et al., 2001, 2005; Lockely et al., 2003, 2006). The proper administration of light is also needed for entraining to new schedules. Light and dark exposure, when administered appropriately, can also serve as an effective countermeasure for maintaining mood and well-being (CIE, 2004; IESNA 2008).

Additionally, the inability to control noise levels can lead to increased stress and a perceived sense of social crowdedness. Constant, monotonous noise and vibration from life-support machinery can interfere with sleep and concentration; crewmembers can also experience subtle, chronic tension as they listen unconsciously for mechanical failure indicated by a change in sound (Bluth and Helppie, 1986; Radloff and Helmreich, 1968; as cited in Suedfeld and Steel, 2000). Individual temperature control is also needed, particularly in private spaces such as crew quarters as some individuals in space have reported feeling too cold, while others indicate feeling too hot. Warm temperatures are known to cause sleep disruption, which can impact performance and well-being.

Mitigations

The interior of the habitat should provide a means for crewmembers to reconfigure layouts and personalize their space to facilitate important psychological aspects, such as individual preferences and cultural differences. In a study of individuals wintering over in Antarctica, Carrere et al. (1991) found that participants personalized his or her living quarters with decorations, paint, new furniture, and reminders of home (Suedfeld and Steel, 2000). In a long-duration mission, being able to reconfigure the living space will further enable personalization, minimize monotony, and allow a sense of control and investment into the living space.

There have been technological advances that facilitate the ability for crewmembers to exercise individual control over important environmental factors such as lighting. An adaptable lighting system that automatically mimics an Earth-day night cycle should be used so that crewmembers can maintain circadian rhythms that enhance optimal sleep times, performance, and health and well being. Research indicates that optimizing the blue end of the light spectrum suppresses melatonin and facilitates phase shifting; when critical work periods fall during adverse circadian phase, these systems should also allow crews to manipulate properties of the light (such as brightness and correlated color temperature) to optimize alertness and performance (Brainard et al., 2001, 2005; Lockely et al., 2003, 2006).

Recommendations for Future Research and/or Technology Development

Below is a proposed list of research and technology activities that could yield habitability recommendations for mitigating some of the stressors related to general and individual control of the environment.

- Efforts are needed to characterize individual control over current environmental systems on the ISS, and its relationship to certain outcomes (e.g., sleep, adaptation, etc.) Analysis of crew feedback would yield insight into lighting systems, temperature, etc. that may lead to expansion of the ranges of control or improvements to current crew quarters design. Preflight testing of recommended options could also be assessed in analog environments.
- Research that informs optimal lighting protocols while increasing safety and minimizing human systems resource requirements (mass, volume, power, data, etc.) is needed.
- Investigate the use and behavioral effects of programmable adjustable lighting parameters (intensity and color temperature) in maintaining circadian cycles while in analog environments deprived of normal day/night cycle, such as Habitat Demonstration Unit (HDU), Antarctica, submarines, or the ISS. Investigate both programmed lighting stimuli to mimic the day/night cycle, and manual settings to allow the crew to actively change the lighting characteristics to establish personalized settings during their own time.
- Conduct a survey of the ISS and other astronauts concerning their desire for reconfigurability of outfitting of their habitable environment.

- Based on feedback, conduct usability testing of various reconfigurable outfitting designs in platforms such as the HDU and Antarctica Stations. Perform microgravity testing of down selected outfitting at the ISS.

3.2.4 Sensory Deprivation and Monotony

Stressors

Sensory deprivation and monotony was identified as a stressor for long-duration exploration missions. Sensory deprivation (SD) is a reduction or removal of stimuli from one or more of the senses (Rasmussen, 1973). The long-duration spaceflight environment provides an isolated, confined, and extreme (ICE) habitat that reduces the amount of sensory stimulation experienced by the crewmember in comparison to Earth (Unpublished NASA white paper Otto, 2006). The human brain requires a steady supply of ample sensory information to remain in good health. *Confinement* is the extent to which group members are physically restricted to a fixed space or geographical area by either man-made or natural barriers, territorial boundaries, or hostile environment. *Isolation* is the extent to which group members are restricted, either by physically or socially prescribed limits, from communicating with others outside the immediate group or from receiving information (Rasmussen, 1973).

Over the past 15 million years of primate evolution, humans have developed a highly sophisticated sensory system in parallel with the vast diversity of the Earth's ecosystems and habitats. The brain receives and integrates incoming sensory information from multiple senses – vision, auditory, tactile, olfactory, gustatory, and kinesthetic or motor. It analyzes, interprets, and stores this data allowing humans to take advantage of novel environments for food acquisition, habitation and procreation to such a degree, that a survival benefit has been conferred by this unique ability (Dominy, Ross & Smith, 2004).

There is considerable evidence that a long-term reduction in sensory input across multiple senses has negative consequences on neural processing and cognition. A constant reduction in sensory input and monotonous stimulation results in a decline in synaptic processes (Vessel & Biederman, 2006, Buckner et al., 1998, Greicus & Menon, 2004). Over time, long-term sensory reduction, in comparison to the baseline Earth-bound condition, causes a decline in biogenic amine levels, required in synaptic neurotransmission, and neural growth factors; this in turn leads to dendritic atrophy, loss of synaptic nerve terminals, and neural atrophy. These neurobiological changes are directly proportional to duration and intensity of deprivation. They ultimately manifest phenotypically as physiological, behavioral, and cognitive changes that can severely impact crew performance during a mission (Unpublished NASA white paper Otto, 2006). Prolonged sensory deprived environments of 6 to 24 months as seen in prisoner of war internment, federal penitentiary solitary confinement, remote duty weather stations, Antarctic research stations, and Russian space stations, have been associated with similar declines in physiological, behavioral, and cognitive functioning (Unpublished NASA white paper, Otto, 2006). The common link between these examples is profound sensory deprivation (and social monotony).

Under conditions of SD, physiological symptoms such as fatigue, insomnia, visual disturbances, and somatic complaints such as headaches, muscle fatigue, and back ache manifest. Behavioral problems such as irritability, aggression, withdrawal, obsessive compulsive behavior, territoriality, paranoia, mild dissociative states, depression and possibly post-traumatic stress disorder develop, the severity depending upon the length of isolation and confinement. Cognitive disturbances include short-term memory loss, difficulty concentrating, prolonged time on tasks and possible visual-spatial effects (Unpublished NASA white paper Otto, 2006).

Mitigations

For future long-duration missions, crewmembers with high aptitude for ICE environments and an ability to function autonomously will need to be selected (Salam, 2010 and Unpublished NASA white paper Otto, 2006).

Further, robust countermeasures aimed at increasing sensory stimulation to all senses without significantly increasing up-mass will be required (Unpublished NASA white paper Otto, 2006). Recommendations for these countermeasures include:

Audio-visual. “Virtual windows” for passive stimulation that are continuously active. These screens can be placed throughout the vehicle in common areas such as the exercise and galley and should be as large as possible. Content should be natural Earth environments from various perspectives. Biederman and Vessel’s study in 2002 measured brain activity through functional magnetic resonance imaging (fMRI) and found that natural Earth scenes provide the most favorable visual stimulation. The British Broadcasting Corporation’s “Planet Earth Series” is a representative example of content. However, thousands of hours of footage would be required throughout the mission. Audio-visual technology should be available for use in personal quarters and used to play a breadth of content from personal videos received from Earth, as well as cultural and sports events of interest to the crewmember. A 3-D headset would increase the realism and depth perception. A large bank of audio files including music and sounds that the crew would typically hear during a year on Earth, such as thunder, traffic, and children playing, should be included.

Olfactory, gustatory, and kinesthetic. An onboard plant growth chamber tended by the crew would stimulate multiple senses during both cultivation and as a food supplement; a spice garden may minimize the volume impact. A suite of olfactory chemical packs with hundreds of pleasant Earth related scents/aromas should be included and released throughout the mission and combined with the common area audiovisual content, if possible, to increase the sensory impact. Interior compartment design should use various materials that stimulate the tactile sense.

Visual, kinesthetic, and cognitive. The onboard aerobic exercise equipment should allow for incorporation of video screen technology so that the running and cycling treadmill becomes a platform to escape to one of hundreds of jogging trails or cycling routes on Earth. Similarly, a virtual reality system would allow crewmembers to engage a larger repertoire of motor patterns and hence motor input through execution of multiple sport/activity patterns. The Nintendo Wii is an example of such a device. Adequate space would be required for a single person to engage in virtual activity and should be in addition to the standard aerobic countermeasures volume so that both can occur simultaneously.

Recommendations for Future Research and/or Technology Development

Below is a proposed list of research and technology activities that could yield habitability recommendations for mitigating some of the stressors related to sensory deprivation and monotony.

- While the benefits of virtual windows have been studied and recognized, they have not been implemented or studied directly as a countermeasure in long-duration analog environments. There is a need to investigate the use of virtual windows and other active sensory stimuli in analog environments like HDU, the Antarctic, submarines, or the ISS. These investigations would aim to characterize the psychological benefits relative to the potential for distraction, measuring overall crew health and performance over long-duration missions.
- Investigate the use of interactive virtual environments including virtual-reality-augmented exercise, as well as virtual worlds with rich visual content such as video games 'Second Life' incorporate technologies into routine exercise or training as part of daily routine.
- Investigate the use of plant chambers and other food related systems in analog environments like HDU, the Antarctic, submarines, or the ISS. Investigate the psychological benefits relative to the potential for distraction, measuring overall crew performance over long duration.

3.2.5 Social Monotony

Stressors

Future long-duration missions will present an historic level of social monotony and isolation. Social isolation refers to the lack of human contact an individual has outside of the crew, whereas social monotony refers to the sameness, and unchanging nature of one's immediate companions (Unpublished NASA white paper Otto, 2006). The need for meaningful social connection and the discomfort experienced due to its absence are defining characteristics of human nature. Individuals experience social connection at several levels. The closest tie to the individual is the family unit; from this central focus, the network expands, to include immediate family and society as a whole (Cacioppo & Patrick, 2008). Once a long-duration space crew is out of view of Earth, they will experience a prolonged and continuous absence of social connections. As humans are a social species, such a lack of human contact will cause profound emotional deprivation that has been found to negatively impact cognitive and behavioral performance (Salam, 2011).

Evolution has shaped our species to feel insecure and even physically threatened when isolated. The sensations of loneliness and separation evolved because it protected the individual from the danger of remaining isolated. As the sense of loneliness increases, so does the vulnerability to stressors, as a result, coping ability decreases. Mental representations and perceived expectations of others become impaired as well as the ability to self regulate. There is a decreased ability to evaluate other people's intentions and an increase in fearful sensations, and distrust. Feelings of isolation can lead to declines in executive control and empathy that result in impulsive selfish behavior. In isolation, the coping mechanism of displacing aggression is less available since there is no one outside the group to whom it can be displaced. Thus, direct expression of aggression is avoided because group members share a high degree of mutual interdependence, consequently, frustration and aggression is internalized and increases the likelihood of developing anxiety, paranoia, and depression (Cacioppo & Patrick, 2008).

Mitigations

Vulnerability to social disconnection varies between individuals. Certain personality types may be better able to adapt to the strenuous environment caused by sensory deprivation and social isolation. Evidence also suggests that previous exposure to ICE environments increases resilience to that setting (Unpublished NASA white paper Otto, 2006).

- Astronauts or astronaut candidates with previous experience in long-duration confinement such as an Antarctic winter-over, the submariner service, or 6-month flights on the ISS should be considered desirable. Individuals with experience in ICE environments may be better able to set realistic expectations regarding long-duration space flight. Spatial limitations and crowding is an intensifier and increases arousal level. In isolation experiments, Taylor et al. (1968) showed that groups receiving privacy and outside social stimulation had reduced stress levels, in comparison to those who did not who rated their stress level as severe and had a 100% dropout rate.
- Privacy and personal crew quarters are essential. People need time to relieve stress in a situation that induces persistent strain. Temporary withdrawal is the primary way that individuals can interrupt the stress-strain cycle that would otherwise be harmful if allowed to persist. Personal privacy is one of the few opportunities crewmembers have to escape the monotony of their daily routine. Personal space allows opportunity to withdraw from interaction, to rest and seek a period of lowered arousal. Consequently, withdrawal becomes a more frequent coping mechanism as a mission continues; the arousal level rises steadily through the mission, therefore the individual seeks withdrawal from the provoking stimulus. Personalization of one's crew quarters is also a compensatory strategy, which allows individuals to have a sense of control over their environment, a place to call their own that is distinct from the vehicle, and removed from other crewmembers (Salam 2011).
- Each crewmember should have his/her own private quarters that can be personalized with their pictures, mementos and belongings. These personal quarters must have the ability to be closed off from others, and they should not be shared. Personal quarters would also provide a private location to view personal audio-video messages from Earth, and record responses. These quarters should have sound dampening properties.

With Earth out of view, the astronauts will feel isolated from the rest of mankind. As social beings, humans have a strong need for connectedness. When we are isolated from our close and meaningful social contacts for prolonged periods our well-being is compromised and individual and team performance suffers (Cacioppo & Patrick, 2008). Individuals who experience isolation are higher in negative state affect, perform worse on cognitive tasks, and engage in maladaptive behaviors.

Astronauts will require contact with family, friends, colleagues, and other significant relations on a regular and frequent basis. Transmitted audio-visual messages from Earth-bound social contacts should be received on a daily basis. Video messaging should include the activities of daily life, updates on a child's hobbies or sporting events, birthdays, other important events, mission milestones, and well-wishes from home. Studies reveal that receiving such contact while under duress reduces serum cortisol levels, a marker of stress activation. Also, celebratory events can ease tension among crewmembers and contribute to a sense of well-being.

Similarly, regular asynchronous private psychological conferences should occur between crewmembers and mission psychologists. In this manner, the crewmember and psychologist can discuss challenges, ways to reframe perceived situations and address faulty cognitions. This would be accomplished using audio-visual messaging in a "Twitter"-like fashion. With the mission psychologist commenting on the crewmember's thoughts and affect expressed in his or her transmissions. In this manner several exchanges could occur over the course of a few hours.

More generally, the use of short messaging services and social media, via handheld devices, to communicate with friends and family will take on increasing importance the further the crew travel from Earth and the greater the telecommunications delay. Short messaging services in particular give the illusion of somewhat instant communication and would probably be very useful yet fairly simple to implement (Salam 2011).

Recommendations for Future Research and/or Technology Development

Below is a proposed list of research and technology activities that could yield habitability recommendations for mitigating some of the stressors related to social monotony.

- Communication modes and frequency should be assessed for effectiveness as countermeasures to social isolation.
- The impact of email, instant messaging, store-and-forward voice transmissions, real-time voice, store-and-forward audio-visual, real-time audio-visual versus face-to-face communication with social contacts, should be characterized.
- Asynchronous audio-visual psychological coaching should be evaluated and perfected as a countermeasure to coping with the stresses of a long-duration mission.
- Technologies to support real-time communications should be developed.

3.2.6 Crew Composition

The workshop community of practice identified that inadequate crew composition posed as a stressor in the exploration environment, and that these stressors could be mitigated via habitability recommendations. Characteristics of the crew such as the *number of crewmembers, their gender, cultural differences, team roles, leadership, relationships, selection, and training* – may have an impact on habitat design. As an example, team size should be considered a determining factor in designing the habitat; if it is anticipated that missions will include four crewmembers, the habitat will require less volume than if eight crewmembers are planned. Quantifying the extent to which the volume scales directly with the number of crewmembers – i.e., at what point increasing the number of crew does not require a volume increase, or as much of an increase – remains unknown. Gender, physical size, cultural differences, and relationships amongst the crew (e.g., whether or not crewmembers are married) represent factors that may interact dynamically between the crew and the habitat, and where future study may be warranted. Other aspects of crew composition, such as training, team roles, and leadership, are critical toward ensuring a successful mission but may not directly impact habitability.

Crew composition is a critical factor in planning for future exploration missions. There is little benefit in having the “right volume” if you have the “wrong crew”.

Stressors

Negative consequences (e.g., incomplete objectives, lost time) that are related to interpersonal stressors such as isolation, confinement, danger, monotony, inappropriate workload, lack of control, group composition-related tensions, personality conflicts, and leadership issues have been observed on previous long-duration missions (Kanas and Manzey, 2003, as cited in Schmidt et al., 2008). Research has consistently demonstrated that interpersonal conflict and tension is the greatest source of stress in Antarctica (Stuster et al. 2000, as cited in Palinkas et al., 2006). Psychological imbalances in just a single crewmember or personality differences between just two individuals during long-duration missions in isolation and confinement can eventually have a profound and negative impact on the group, even if the remainder of the group is composed of well balanced and adapted individuals (Salam 2011). Such negative events include social marginalization, reduced group consensus, and eventually risk to mission. Thus selecting individuals based on both personal characteristics and their interaction and compatibility within a specified team unit is critical.

Mitigation

As noted by Schmidt, Keaton, Slack, Leveton and Shea (2008), many researchers suggest that the composition of a team has a major impact on how successful that team is likely to be. Kanas et al. (2001) evaluated Shuttle and Mir missions and found that composing an interpersonally compatible crew is an important countermeasure for potential psychosocial problems. Although selecting a crew for interpersonal compatibleness is preferred, operational constraints have severely limited spaceflight research opportunities. Furthermore, there is no empirical evidence from either U.S. spaceflights or international spaceflights that indicates how best to compose crews that have both the right technical competencies and the right interpersonal mix to achieve optimal performance. Given that a long-duration exploration mission will likely consist of a mixed gender, mixed-cultural crew, aspects of the spaceflight environment should allow for reconfiguration (as discussed in 3.2.1 and 3.2.3).

Recommendations for Future Research and/or Technology Development

Research has been conducted on this topic in various analogs; data mining efforts should inform crew composition recommendations. A gap in the literature however remains: few studies have observed team and individual outcomes under varying crews over long-durations in isolated, confined, and extreme environments. Hence, one habitat recommendation based on crew composition requirements may be sufficient for a short-duration stay, but whether those findings can be applied to long-duration missions remains unknown. Below is a proposed list of research and technology activities that could yield habitability recommendations for mitigating some of the stressors related to crew composition.

- Holland and Galarza (1999) found that the recommended characteristics of the ISS astronaut vary from the recommended characteristics of a Shuttle astronaut. Likewise, the long-duration exploration crewmember will face different challenges than today's flyers. A greater emphasis should be placed on characterizing astronauts with an aptitude for long-duration missions, well beyond the current paradigm of 6 months of real-time operations on the ISS. An evaluation of candidates with experience in autonomous long-duration environments should be conducted to inform this gap.
- Investigations looking at the adaptation of the individual and the crew to the physical environment and the role of that environment (the volume, layout, privacy, common areas) on the crew should be conducted, in high-fidelity analogs.
- Research related to cultural differences among a crew and how these can be accommodated via habitability requirements are needed. These investigations could be conducted in analog environments as well as ISS.
- Efforts are needed to translate crew composition requirements into habitat recommendations; i.e., if crewmembers are married to one another, then the configuration shall provide certain characteristics; also, as mentioned above, quantifying the relationship between crew size and volume.
- Team units need to be selected and tested in analogous isolated and confined environments (such as Antarctica and subaqua habitats) for long-duration missions.

3.2.7 Physiological and Medical Issues

Stressors

The workshop community of practice identified that physiological and medical issues are factors to consider when designing the habitat for exploration missions. In particular, the potential lack of hygiene separation will have an impact on habitability requirements. Other stressors were discussed, most of which were addressed through other habitability requirements.

Mitigations

The requirement for cleanliness is highest in the medical and galley area that has the greatest likelihood of contamination if collocated near either the hygiene/toileting facility or the exercise area. Therefore adequate separation should exist between these spaces, with the hygiene/toileting facility located as far from the medical and galley area as possible, with an added benefit of providing greater privacy to personnel.

The medical and patient care area will require sufficient volume to store and deploy the medical equipment needed to provide patient care, including diagnostic, treatment, and laboratory hardware, as well as restraints for the patient, crew medical officer (CMO), and deputy CMO. Technologies will be designed to facilitate the CMO's clinical situational awareness of the patient's status to effect treatment and anticipate next steps. Capabilities will include high-resolution cameras that can be positioned to image any area of interest on the patient, a large display monitor with the ability to provide split screen views, and videoconferencing with the ground medical team. In addition, the CMO's personal quarters should ideally be placed within close visual proximity of the patient care area.

A galley space provides a location for food preparation, group meals, and a meeting place. The requirement for food preparation and some food storage will demand a commensurate level of hygiene. Therefore, location of the galley between the medical facility and the science lab will allow crew to maintain a high level of hygiene in the galley. As a common area, display screens in the galley will allow for viewing of incoming audio-visual communications and for viewing of recreational content. A small plant growth chamber in the galley, or possibly the science lab, would provide additional sensory stimulation, of a pleasant nature, in a common area and allow the crew to easily tend the growth chamber daily.

A science lab space on the vehicle will be necessary for crew to engage in meaningful work during transit. This space should allow for multiple science functions so that all crewmembers could conduct activities here, with the exception of the CMO who could work in the medical care area. However, size constraints may limit the number of crewmembers that could use the science space simultaneously and the available scientific equipment and reagents.

The exercise facility would be well situated if it were located in an adjoining module to the science lab, perhaps even as a separate space. Separation of the exercise space would limit noise transfer during use. The exercise facility should allow for incorporation of video screen technology so that the running and cycling treadmill becomes a platform to view numerous videos of jogging trails or cycling routes on Earth. Space for a strength training hardware will be required. In addition, the minimum space required for single person or possibly dual person body movement using a virtual reality system would allow crewmembers to engage in a larger repertoire of motor patterns beyond the fixed exercise equipment, and thus vary the breadth of motor input through execution of multiple sport/activity patterns. Space for dual capability would allow two crewmembers to compete/play against one another if desired.

Given the physiological implications of poor sleep and increased stress, recommendations discussed in Section 3.2.1 and 3.2.4 are also relevant when considering the physiological and medical aspects of habitat design.

Recommendations for Future Research and Technology Development

Research and technology activities related to telemedicine may yield habitability recommendations for mitigating some of the stressors related to physiological and medical issues. Further discussions with NASA medical community can yield insight into additional considerations that may alleviate risk during future missions.

3.2.8 Contingency Readiness

Planning to resolve emergency situations will be critical to ensuring the success of future exploration missions. The workshop participants identified *lack of a back-up plan* and *lack of rescue scenario* as stressors for long-duration exploration missions. These stressors were then categorized as "contingency readiness." As discussed by the workshop community of practice, a long-duration mission to unexplored destinations should include provisions that are made available in case of an emergency. Volume and habitability recommendations will be required to support such resources.

Stressors

A back-up plan can provide rescue, and hence peace of mind, to a crew on a planetary expedition. The no rescue/abort scenario is a subtle stressor in ICE environments such as Antarctic stations where crews often have no possibility of evacuation for up to 9 months. This stressor is not necessarily felt until a life support emergency or failure occurs, at which point the fear of total isolation and threat to life can sometimes lead to a lasting sense of anxiety in some crewmembers (Salam 2011).

Following the Challenger accident in 1986 (during which there was no escape hatch), NASA developed an emergency escape hatch for the Shuttle fleet that enables crewmembers to exit from the side of a Shuttle on a parachute during certain types of emergencies in the later parts of a landing. Aboard the ISS, resident crews have access to a modified Russian Soyuz spacecraft as an emergency rescue vehicle should they need to leave the outpost. Similarly, NASA adopted "anytime abort" requirements for the Constellation Lunar program, ensuring resources to permit anytime return en route to the moon or from the lunar surface.

On a similar, but lesser scale note, back-up plans to support other aspects of a mission, should be put in place. As an example, in 2004 astronauts living on the ISS were beginning to run out of food and had to cut back on their daily caloric intake. This shortage was attributed to a drop in supplies resulting from the grounding of the Shuttles following the Columbia accident. While this incident did not result in a performance or health decrement, in the context of a future long-duration exploration mission, adequate stowage and provisions need to be made available for contingency situations that may arise. Indeed adequate volume needs to be accounted for in terms of back-up equipment and materials, and mission prolongation, during habitat design. Experience from highly isolated Antarctic stations without possibility of delivered for prolonged periods suggests that, even under such circumstances, planning for sufficient materials and equipment failure is still often inadequate and underestimated by both individuals and research groups.

Evidence from historical arctic expeditions indicates that stringent contingency preparations are needed to support high risk missions in extreme environments (Stuster, 1996). Fridtjof Nansen and his Norwegian Polar Expedition, for example, have been considered the model expedition for all subsequent polar explorers (Stuster, 1996). The success of this mission is largely attributed to Nansen's systematic simulation, testing, and evaluation of every item of equipment, and meticulous attention to every detail and possible contingency (Stuster, 1996). This careful consideration included Nansen's theory based on previous failed expeditions that the ice cap at the Arctic moved in a westerly direction. Rather than take an existing vessel and attempting to resist the pressure of the ice caps as previous explorers had done, he built a new ship that would be physically adaptable to navigate in such an environment (Stuster, 1996). While it required a greater investment, the vehicle was successful in taking the crew to their destination and returning them home.

Mitigations

Mitigations for contingency planning in the crew vehicle include:

- Ensure adequate supplies for a long-duration mission, perhaps through the provision of cargo vehicles.
- Ensure that supplies are not stowed in any one, single location, in case something happens to that location.
- Redundancy of ships and/or pressure volumes, and equipment/materials. Rather than complete the mission with one vehicle carrying all crewmembers, provide an additional vehicle as a back-up for an emergency situation. One proposed configuration: connect two "Orion" type vehicles to a station module. The successful return of the Apollo 13 crew using the redundant systems from the Lunar Excursion Module following an explosion in the Crew and Service Module is an example of such a solution.

Recommendations for Future Research and/or Technology Development

Discussions with NASA contingency coordinators can yield insight into additional considerations that may alleviate risk during future missions.

3.3 Mitigation Strategies and Recommendations

One of the top level objectives of the workshop was to initiate the process of collecting enough information about the stressors and their impact on habitat design and layout to enable later prioritization of future research. To achieve this prioritization, it will be necessary to first understand the stressors fully and the extent to which the stressors must be mitigated. There must be sufficient evidence that the stressor is a driving habitability/design consideration and that the identified mitigation methods are sufficient and effective. Concurrently, the potential impacts to habitat designs should also be captured as part of the prioritization of the stressors. It was also desired to identify potential analog test platforms that could be used to validate the effectiveness of stressor mitigation strategies and the metrics used to capture performance on certain stressors. Initial attempts to provide information necessary for future prioritization efforts were captured in the psychological stressors matrix included in Appendix D and the following sections.

3.3.1 Habitat Design Recommendations

Although many of the identified stressors require additional research before definitively deciding if mitigation methods are necessary or effective, workshop participants did identify some stressors and mitigation methods that could and should be implemented without additional research. These types of mitigations fall into two categories:

1. Easily achievable mitigations with minimal design impacts
2. Mitigations for extremely well understood, critical stressors

Easily achievable mitigations are those that are both affordable and are relatively easy to implement without significant changes to interior layouts or additional equipment. The easily achievable mitigations discussed frequently at the workshop include, but are not limited to:

- Providing a common area to accommodate dining/recreational activities for all crewmembers simultaneously
- Providing a common area to accommodate work activities for all crewmembers simultaneously, with options to place partitions around personal workstations
- Providing a means for communicating with those on the ground (including private communication channels and noise control) will need to be made
- Including real or virtual windows, video goggles, or other technologies that can provide an immersive, sensory rich experience
- Providing environmental control and protocols for utilizing environmental factors (e.g., lighting) to optimize health and performance

A few highly critical stressors that substantially impact crew psychological health were also identified by participants.

- Providing private, personal space to decrease overall stress led to the recommendation of providing personal crew quarters with additional steps to ensure privacy and minimize perceived crowdedness, such as noise and vibration buffering. The ISS crew quarters were described as adequate for this purpose, though long-duration crews in smaller habitats may require larger individual quarters.

Note that mitigations identified in this section are not comprehensive, but represent those agreed upon at the workshop as mitigations that could be implemented without further research. A full listing of the stressors and mitigations discussed may be found in Table 3. Prioritization of the mitigations to be implemented requires additional research and remains as future work.

3.3.2 Research Recommendations

Research to address the stressors takes two forms:

1. Improves the understanding of the stressor and its relative importance compared to other stressors
2. Tests and improves mitigation methods for each stressor

The first research activity is a risk characterization effort. This allows for prioritization across the set of stressors by understanding the risks associated with the stresses placed upon the astronauts. The second allows for further prioritization by characterizing the difficulty or cost of effectively mitigating the stressor. By performing both types of research activities, future research and development efforts can be prioritized on a risk basis, and the effect of recommended mitigations can be determined relative to mission design, habitat design, and operations. Table 3 contains the initial thoughts from the workshop on future research that could be performed to address each stressor. These are arranged by mitigation method to map future research to the potential mitigation methods identified in the previous section. Detailed thoughts capturing potential stressor research were included in Section 3.2.

Table 3 Design and Research Recommendations Out of Workshop

Psychological Stressor Category	Habitat Design Guidance	Research Recommendations
Allocation of space (H)		
Lack of Personal Space / Lack of Private Space	Provide individual, separate sleeping/personal quarters w/auditory isolation (mandatory) and physical separation (if possible) for each crewmember	• Noise abatement • Volume acceptability testing of private crew quarters • Airflow, velocity, temperature of air conditioning system in crew quarters
	Isolated locations throughout the vehicle	• Assess "perceived" personal space and privacy under different layouts
	Separation of private spaces from spaces allocated for common, social areas and congested translation paths is preferred	• Assess "perceived" personal space and privacy under different layouts
	Visual separation of private spaces from each other to allow for perception of increased privacy	• Assess "perceived" personal space and privacy under different layouts

Psychological Stressor Category	Habitat Design Guidance	Research Recommendations
	Rotating shifts	• Assess "perceived" personal space and privacy under different layouts
Feeling of "Crowdedness"	Separation of high traffic function	• Clear definition of operations assumed during mission with detailed schedule could allow for analyses to layout interiors with significantly reduced crew congestion or crew displacement. • Development of scheduling tools that incorporate layout considerations; testing of these scheduling tools
	Appropriate task scheduling/ task location	
	Dedicated translation paths in integrated environment	
	Increased volume or other dimensions to increased actual/perceived space	
	Rotating shifts	
Lack of Privacy of Waste & Hygiene Compartment	Dedicated, private area for waste and hygiene with hygiene areas away from dining area and medical station	• Could potentially determine actual volume # • Determination of # of bathrooms (presumably based on crew size)
	Separation of WHC area from translation areas	
Workspace (H, L)		
Lack of Meaningful Work/Activity	Provide individual development plans for each person's work goals, progress, and achievements	• Determination of the appropriate level of crew autonomy and selection of tasks for greater crewmember satisfaction
	Allocation of space and resources to accommodate each individual's work and activities (i.e., science, laboratory equipment, electronic curriculum, etc.). Each individual should have their own workspace and materials should be appropriately placed for ease of use and improved functionality	• Need list of activities to be performed on long-duration missions to inform designers of necessary equipment, crew composition, and scheduling requirements • Develop individualized goals for each crewmember to ensure meaningful activities
	Volume will be needed to hold samples and toolkits for in-flight experiments. Other features to impact volume may include electronic equipment to store data (workstations and hard drives) and a telescope. Equipment needed for analysis of collected samples during inbound flight.	• Systematically assess current NASA processes for providing crewmembers with hardware and electronic resources. How are these ensured to fit within specific parameters?
Sense of Poorly Placed Stowage	Ensure stowage types are near designated areas (i.e. food near dining)	• Leverage ISS experience with stowage and consider placement for function and performance early in designs
	Ensure that not all materials are stowed in one place	
General and individual control of environment (L)		
Lack of Individual Controls Over Temperature, Ventilation or Lighting	Place individual controls and distribution vents in crew quarters and at workstations	• ISS - record use of individual controls of lighting and comments that would lead to expansion of the ranges of control or improvements to current crew quarters design

Psychological Stressor Category	Habitat Design Guidance	Research Recommendations
Lack of Reconfigurability for Cultural Difference / Personal Space Preferences	Reconfigurable packaging for crew accommodations and furniture	• Survey of ISS and other astronauts concerning desire for reconfigurability of outfitting. • Usability testing of various reconfigurable outfitting designs • Simulations; Antarctica stations and HDU • Microgravity testing of down selected outfitting at ISS
	Modular design with multiple applicable locations for multiple activities	• Simulations; Antarctica stations
Sensory deprivation and monotony (L to M)		
Lack of Stimulation / Sensory Variability	Windows (Provide visual stimulation of high quality close to Earth, but limited utility on long-duration transit missions)	• Data mining; assess effects on behavioral outcomes
	Virtual Windows - Camera with projections of space, video of terrestrial footage, telescope,	• Deploy in remote, long-duration environments; compare behavioral health outcomes
	"Holodeck" or other virtually immersive environment	• Development and testing in long-duration environments, i.e., Antarctica
	Increased spatial vista within habitat	• Study to characterize the impact of spatial vista on psychological acceptability
	Lighting, colors, and other visual countermeasures to increase sensory stimulation	• Development of systems for spaceflight
	Greenhouse or other introduction of plants and natural elements for tactile, visual, gustatory, olfactory	• Determine to what extent plants address these sensory systems so can develop other CM if these are not sufficient
	Different surfaces in the interior to maintain tactile senses	
	Provision of musical instruments and music selection to counteract auditory	• Interview flyers, others in LDM to identify what works/doesn't work about this and other recreational CM
	Enhance exercise system to include virtual experience	• Development of systems for spaceflight
	Allocation of space for exercise equipment and "stretch-out" room	
Social monotony (L)		
Social Deprivation / Lack of Common Areas	A common area for recreation, large enough to accommodate all crewmembers inside at the same time	• Comparison of crew interactions in habitats with variations of group spaces
	Include 'television' (or equivalent) for crew to watch movies together (movies in the form of data can be transmitted from Earth to also provide sensory stimulation)	

Psychological Stressor Category	Habitat Design Guidance	Research Recommendations
	A common area for dining, large enough to accommodate all crewmembers dining inside at the same time. This can be the same as the common area for recreation (converted). Kitchen required for food preparation.	
Limited Communication with Home	Communication system should be provided in each private quarter	
	System that facilitates voice and text should be provided	• Development of systems for spaceflight
	Space for a "holodeck" to provide visual and auditory connection with loved ones at home.	• Development of systems for spaceflight
	Private space with pictures of family members	
Crew composition (H)		
Crew composition may be a cross cutting / high level driver / overarching category that impacts several other stressors in other categories, and can be addressed via other habitat requirements. Input and suggestions are welcome here.	Characteristics of the crew (team size, gender makeup, job roles, and cultural backgrounds) that are established before the mission and will not change as a result of the mission should be considered when defining the habitat requirements.	• Data mining (data and anecdotal evidence from space flight and other international agencies) to determine things such as: - if married, then configuration shall ____ - if two males and two females, then configuration shall______ - if three crew then configurations shall ____
Physiological and medical Issues (M)		
Lack of Hygiene Separation	Provide separation between clean areas (medical treatment, food prep, crew quarters, etc.) and dirty areas (hygiene, dusty areas, etc.) Medical treatment area may need to be separate as a biological contaminant (dirty) and a sterile (clean) area.	• Implement on future layouts
	Provide olfactory or other partitions to prevent contamination of clean areas. This can include closed, separately ventilated areas.	
Contingency readiness (M)		
Lack of "Backup Plan" / "Rescue Scenario"	Recommendation to have separate modules (recommendation for redundant ships that are connected; two Orion vehicles with station module in the middle.)	
	Placement of hatches to allow for alternate escape routes. Provision of radiation shelter	

3.3.3 Analog Characteristics Identified in Workshop

The research identified above must be performed in a laboratory or analog test environment suitable for characterizing the stressor or mitigation method in a technical and cost-effective manner. Each of the potential test locations currently available has particular characteristics that serve as discriminators for choosing the most appropriate analog. These characteristics include but are not limited to the following:

- **Physical Isolation:** The degree to which an analog is truly isolated from other humans, potential resupply, and immediate extraction in the event of an emergency.
- **Mission Duration:** The length of time that can be tested in the analog, typically limited by available stowage and other similar constraints.
- **Reconfigurability of the Interior:** The degree to which the interior of an analog can be customized to aid the study of configuration dependent phenomena.
- **Crowdedness/Net Habitable Volume:** A measure of the free volume available relative to the number of crew that describes the potential for crowding or physical interference between crewmembers.
- **Control of the Environment:** The ability to control the operational ground rules constraining the study, including but not limited to the operations schedules, atmospheric comfort settings, and other important parameters.
- **Mission Tempo:** The inherent pace of work during a mission in the analog that could be either desired or prohibitive for the stressor being tested.
- **Communications with Outside:** The degree to which communications with the outside world are limited, often by extending communications delay.
- **Microgravity:** Indicates if the analog is in a space environment necessary to test certain microgravity configurations/activities.
- **Inherent Sensory Deprivation:** The degree to which visual, aural, olfactory, gustatory, and tactile stimuli are lacking in variety.
- **Availability of Medication / Medical Care:** The difficulty of obtaining medication or competent medical care.
- **Workload:** The typical workload imposed upon participants.
- **Team Size:** The number of crewmembers that a participant will interact with.
- **Personal Space:** A measure of the private space afforded to each crewmember.
- **Cost**: The expense of operating or using an analog.
- **Perceived Risk:** The level of real or perceived personal danger in the event of contingencies or systems failures.

Each of these characteristics can then be used to map each of the stressors to the most appropriate analog choice. The suggested process for this mapping is to rate the analog's performance on each of these criteria using some standardized rating scale or pair-wise comparisons. This will create a profile of the strengths and weaknesses of each analog, which can be compared to the desired characteristics to effectively test each stressor to identify the best fit. This analysis is future work. The analogs under consideration include:

- Earth-based Laboratories
- Foam/Wooden Mock-ups

- NASA 20-foot chamber
- Habitat Demonstration Unit (HDU)
- NEEMO (and other undersea habitats)
- Submarines
- Antarctic Analogs (Concordia, McMurdo station)
- International Space Station
- Notional New Deep Space Vehicle Testing Platform

As an example of the identification of the best analog, assume that an Antarctic Analog rates well in Isolation, Mission Duration, and Communication with the Outside World, which are critical characteristics for characterizing social monotony and its mitigations. In this case, the Antarctic Analog would be chosen to test social monotony provided that no cheaper or easier alternative analog could also serve as the test location. In general, the lowest cost solutions for testing each stressor should be investigated. Similar processes for choosing between analog alternatives can be found in Keeton et al. 2010 that describes the NASA Behavioral Health Program's Analog Assessment Tool.

As a final note about analogs, the aforementioned analogs only include existing alternatives. Any additional facilities that can be developed to test the stressors are desired, particularly if there is no existing analog with the characteristics required to test a stressor. Additionally, existing solutions should be chosen with consideration of factors not analogous to human spaceflight in addition to the identified criteria. For example, while Antarctic stations offer long-duration and confinement that render this analog useful for evaluating the behavioral outcomes, there are factors that are not analogous to spaceflight (e.g., crew size, darkness, access to the outside, participants) that limit its utility. The recently completed Russian Mars 520-Day Study, sponsored by the Russian Space Agency, provided a unique opportunity for the National Space Biomedical Institute along with investigators from other international space agencies to observe and collect data on a small crew in a mock-up habitat, over a long-duration simulation to Mars. While this effort will yield insight into risks faced by exploration crews, there remain limitations, including a small sample size and questions surrounding the numerous concurrent investigations that may have, to some extent, influenced one another. NASA should consider developing new analogs, or improving the fidelity of existing analogs to better represent the conditions of long-duration, deep space missions before finalizing mission or habitat design for these missions.

4. Findings and Observations from the Workshop

The workshop was successful in achieving its primary objectives, due in large part to the collaboration across disciplines and the unique analog experience represented by the participants, which greatly contributed to a consensus on the completeness of the information gathered. Psychological stressors were first identified, then filtered to the subset that impact habitat design, and characterized further to aid in informing the existing integrated research plan (IRP). Potential mitigations and research recommendations were then identified for each stressor. A full summary of these findings may be found in Table 3. In addition to these accomplishments, several other observations from the workshop were identified as potentially useful to the community of practice.

Layout versus volume. First, it was determined that most psychological-behavioral health stressors were more dependent upon layout considerations than on overall internal volume. This indicated that the definition of many layout dependent factors (including but not limited to habitable volume) would be required to mitigate potential stressors. For instance, the perception of crowdedness might be mitigated by a shift schedule or privacy partitions as opposed to simply increasing the volume.

Need for concept of operations. It was further determined that to determine these layout dependent factors, an internal layout concept was needed. This is normally created later in the study cycle, during preliminary design, because additional concept definition data must be available. Missing data at this early study phase includes crew schedules and the necessary functions for the specified mission. A resultant recommendation from workshop community of practice was to start a long-duration concept of operations that is necessary to define crew schedules and required functions. Once these data are collected and layout concepts are created, their role in defining the psychological acceptability of habitats will be better understood. Simon 2010 proposes a process that would allow for the inclusion and optimization of these layout-dependent factors in the habitat conceptual design process. This and other existing work on exploration mission design will be leveraged in the future.

Overlapping task volumes. Another recommendation from the workshop was that additional work to identify the habitable volume required by overlapping of individual task volumes as an independent, first-order approximation of the necessary habitat volume is a desired body of work. This was deemed the most appropriate method for volume requirements determination. It would require the addition of input from members of the anthropometrics and ergonomics standards community, as well as subsystem experts from the ISS program to define the volume required for effective task performance of the tasks in a more advanced, long-duration system. Particular driving functions for determining volume include exercise, private crew quarters, stowage, airlocks, and an equipment maintenance area.

Interim volume recommendation. It was determined that a universally acceptable numerical volume recommendation could not be provided, especially one that is independent of the layout concerns and psychological mitigation strategies identified in this report. However, it was possible to identify the range of possible values that this volume recommendation should fall within using the existing literature and existing spacecraft. The "average curve" shown in Figure 1 should provide the minimum limit for reasonable recommendations for long-duration missions as any performance decrements would be unacceptable. For the maximum recommendation:

"The habitable volume values for existing spacecraft represent proven solutions for particular durations. Designs at these volumes are 100% feasible, though it is important to note that this

100% feasibility limit does not ensure a design without crew impairment. Requirements and design reference documents should be consulted to provide recommendations for habitable volume values with the understanding that, within these boundaries, considerable flexibility must be tolerated." (Simon, 2011)

Additionally, it is necessary to consider that these values may change for varying gravity environments and interior configurations, so some amount of flexibility should be used for current recommendations until these factors can be adequately studied.

5. Forward Work and Research Plans

The identified future work focuses on research and tasks to aid in addressing the gaps identified in this report. This includes developing interior layouts and habitat sizes for the habitat design and evaluation communities, determining that aspects of the identified list of stressors need to be added to the existing HRP integrated research plans (given that some of the proposed tasks are being addressed through the BHP and Space Human Factors and Habitability [SHFH] Elements), prioritizing the proposed research for the HRP, and recommending research areas for the analog testing community.

One outcome of the workshop was the establishment of a team to develop a long-duration habitation concept of operations to inform crew schedule and interior layout analyses. This group will focus on identifying crew activities and knowledge gaps in our understanding of human operations during long-durations. Future work related to this activity includes elicitation of information from the crew scheduling communities (particularly the ISS and submarine) and development of layout concepts to understand the layout specific stressor mitigations necessary and how they impact the design of habitable spaces.

To create a human or analog testing research plan with maximum utility to the stakeholders (particularly habitat designers for future exploration concepts), the stressors and mitigation strategies contributing to habitable volume definition and interior layout rationale should be reviewed by the stakeholders and prioritized by their overall impact to stakeholder interests (such as importance to habitable volume determination or other substantial benefits). This list will then need to be balanced by the cost of the research and an assessment of when for inserting the results of this investment would be most beneficial. Any easy to achieve or highly critical factors should be recommended for investment, while less critical items should be reserved for later consideration. No specific recommendations beyond those in this document have yet been provided.

Although some tasks in the research plan will be highly dependent on the chosen exploration strategy and missions, there are some overarching areas of research identified that will need to be pursued in some fashion. These include the following:

- Prioritization of the knowledge and mitigation gaps identified
- Development of methods and/or test beds allowing for future testing on the ISS

- Identification of effective and practical metrics, methodologies, and tools for determining and assessing habitable environment and layout (including assessments in analog environments)
- Development of reconfigurable spaces and crew accommodations consistent with mitigation strategies
- Identification of the number and types of crewmembers required for the exploration missions with the goal of identifying the minimum capability and space requirement for different crew size (number of crew) and mission duration combinations.
- A long-duration confinement and isolation study for durations on the same order as the desired exploration missions that:
    - Maintain fidelity to a planned mission: small isolated crew, analogous to the exploration astronaut
    - Focus on characterizing psychological stressors and the social dynamic between crewmembers

The primary objectives of the workshop were met, defining a set of stressors and potential mitigations impacting design and volume requirements. Those that can be used immediately have been provided to the team expanding on the HEFT's results. Those that require more research have been reviewed from the perspective of the BHP and SHFH and are being folded into the existing IRP and forward planning. While much work remains, the workshop findings serve as an anchor point from which future work may be done.

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Appendix A: Acronyms

BHPT	Behavioral Health and Performance Team
CMO	Crew medical officer
fMRI	functional magnetic resonance imaging
HDU	Habitat Demonstration Unit
HEFT	Human Exploration Framework Team
HHP	Human health and performance
HIDH	Human Integration Design Handbook
HQ	Headquarters
ICE	Isolated, confined, and extreme
IRP	Integrated research plan
ISS	International Space Station
JSC	Johnson Space Center
LaRC	Langley Research Center
LEO	low-Earth orbit
MSFC	Marshall Space Flight Center
NASA	National Aeronautics and Space Administration
NESC	NASA Engineering and Safety Council
SD	Sensory deprivation
STD	Standard
TFT	Tasks and Functions Team

Appendix B: Workshop Participants

Name	Organization	Background
Larry Toups^	NASA JSC	Workshop Co-Chair ; LSS, LAT, CAT, HEFT Habitation lead; workshop planning team
Janis Connolly	NASA JSC	Workshop Co-Chair; HRP-SHFE Project Manager, including HIDH and HSIS (NASA STD 3001) development; workshop planning team.
Jack Stuster, PhD^	Anacapa Sciences	Principal investigator with BHP Research, recently completed ISS Journals Study; expert in arctic explorers, habitat/behavioral health; has provided human factors support for the design of space stations, lunar bases, interplanetary space craft, Navy airships and submersibles, Air Force rail cars, command and control centers, and monobaric underwater habitats.
Alex Salam, MD^	European Space Agency	Medical doctor; spent ~14 months at Concordia Station in Antarctica with about 12 or so other individuals; spoke at last year's Humans in Space conference; affiliated with the European Space Agency.
A. Scott Howe, PhD^	Jet Propulsion Laboratory	Space architect, Jet Propulsion Laboratory
David Liskowsky	NASA HQ	Director, Medical Policy and Ethics; Neurolab Special Projects Scientist
John Connolly, PE	NASA JSC	20+ years of human exploration studies; Deputy Manger EMSO
Lauren Leveton, PhD	NASA JSC	Behavioral Health and Performance Element Manager in the Human Research Program
Craig Kundrot*^	NASA JSC	HRP Science Management Office; workshop planning team
Mike Foale, PhD	NASA JSC	NASA Crew Office
Jeff Williams, Col. USA, Ret.	NASA JSC	NASA Crew Office
Lee Morin, MD, PhD	NASA JSC	NASA Crew Office, submariner
Andy Thomas, PhD^	NASA JSC	NASA HEFT In-space Elements Lead, Astronaut STS 77, 89, 102, 114, aboard Mir for 130 days. Workshop planning team.
Walter Sipes, PhD^	NASA JSC	Clinical psychologist for ISS crewmembers. Expert in human factors, sleep, workload, cognition, and operational psychology. Workshop planning team
Nigel Packham, PhD^	NASA JSC	First 10-day crew study; 15-day sealed crew study
S. Richard Ellenberger^	NASA JSC	Habitability and Human Factors Branch

Name	Organization	Background
Jonathan Dory*^	NASA JSC	Acting Chief, Habitability and Human Factors Branch; workshop planning team
Susan Baggerman	NASA JSC	Habitability and Human Factors Branch
Robert Howard, PhD	NASA JSC	HDC, Habitability and Human Factors; workshop planning team
Kriss Kennedy, Licensed Architect	NASA JSC	HDU Manager, TransHab
William "Rod" Jones^	NASA JSC	ISS; Former Flight Crew Systems and Integration Subsystem Manager, Initial Design of Space Station
Al Holland, PhD*	NASA JSC	Organizational psychologist that provides psychological support during ISS missions; also served as crew psychologist during Mir. Experience also working with military crews. Participated in habitat experiments in the 90s at NASA; workshop planning team.
Gary Spexarth	NASA JSC	TransHab Structural Design; workshop planning team
Sandra Whitmire^	Wyle Integrated Science and Engineering	Lead for BHP Research, Bioastronautics Contract; Risk Area Manager for Sleep/Circadian research; workshop planning team
Sherry Thaxton, PhD^	Lockheed Martin	HRP SHFE principal investigator
Stephen Hoffman, PhD^	Science Applications International Corporation	Senior systems engineer; over 20 years of long-duration human planetary mission planning (trajectories, propulsion, surface systems for humans) and comparative studies of polar exploration on Earth.
Camille Shea, PhD	Universities Space Research Association	Behavioral Health and Performance Element Scientist in the Human Research Program
Stephen Vander Ark, MS	Wyle Integrated Science and Engineering	Behavioral Health and Performance Section Manager
Marianne Bobskill, PhD*	NASA LaRC	Exploration habitation; Workshop planning team
Matthew Simon, PhD^	NASA LaRC	HEFT Habitation IDL, parametric habitat sizing; Workshop planning team
Hank Rotter*^	NASA NESC	NASA technical fellow; expert in crew and thermal systems with experience beginning during Apollo and continuing to current day
Andy Cameron, PhD	National Science Foundation	NASA consultant and Arctic logistics engineer, Antarctic experience
Jack Stokes^	Retired NASA MSFC	Tektite crewmember

Name	Organization	Background
Peter Suedfeld, MD	The University of British Columbia	Suedfeld's work with reduced stimulation has included everything from simple quiet rooms, through solitary confinement in prisons and capsule environments planned for space, to the near-absolute reduction in stimulation obtained with the restricted environmental stimulation technique.
George Brainard, PhD^	Thomas Jefferson University	NSBRI Human Factors and Performance Team lead; expert in neuro-endocrine, circadian, and neurobehavioral effects of light
Larry Palinkas, PhD^	University of Southern California	Medical anthropologist who has been working with NASA for several years. Has studied Antarctica; primarily studies of psychosocial adaptation to extreme environments.
Yvonne Masakowski, PhD^	US Navy	Lead human factors psychologist, Naval Undersea Warfare Center
Teresa L. Miles^	US Navy Naval Sea Systems Command (NAVSEA), Submarine and Undersea Systems	Technical warrant holder for arrangements (submarines). Expert in arrangements that includes hardware, system and logistics arrangements, as well as habitability (including mixed gender crew) arrangements, human systems integration /human engineering (as applied to arrangements), and flow paths.
Christian Otto, MD	Universities Space Research Association	Senior scientist with BHP research; served as station physician twice during the Antarctica winter. Collected data looking at stressors and behavioral outcomes while at South Pole Station and McMurdo.

*Helped to plan, but did not attend workshop
^Provided written material and/or presentations

Appendix C: Workshop Agenda

Monday April 18	Tuesday April 19	Wednesday, April 20	Thursday, April 21
	8:30-9:00 Morning Coffee	8:30-9:00 Morning Coffee	8:30-9:00 Morning Coffee
	09:00-10:30 **Crew Forum** Astronaut(s) Brief overview from crew; questions/answers with Workshop participants	09:00-10:30 **Workshop Discussion Teams** **Berkner Room Breakouts** Teams 1-2 Development of Volumetric parameters to mitigate psychological stressors Teams 3-4 Functions/Tasks and Volume Drivers Parameters	09:00-10:30 **Workshop Debriefing** and development of forward work (*Workshop Development Team*)
	10:30-10:45 Break	10:30-10:45 Break	10:30-10:45 Break
	10:45-12:00 **Workshop Discussion Teams** **Berkner Room Breakouts** Teams 1-2 Identification of Psychological Stressors & Mitigation Strategies Teams 3-4 Functions/Tasks and Volume Drivers Identification	10:45-12:00 **Workshop Discussion Teams** **Berkner Room Breakouts** Teams 1-2 Development of Volumetric parameters to mitigate psychological stressors Teams 3-4 Functions/Tasks and Volume Drivers Parameters	10:45-12:00 **Workshop Debriefing** and development of forward work (*Workshop Development Team*)
12:00-1:00 **Registration** – USRA Rotunda	12:00-1:00 **Lunch** @ USRA Ordered From BJ's Deli (can be working lunch)	12:00-1:00 **Lunch** @ USRA Ordered From BJ's Deli (can be working lunch)	12:00 **Conclusion of Workshop Debrief**
2:30-4:30 **Presentations By Workshop Participants** Introduction By Community Of Practice Addressing Habitable Volume	3:00-3:15 Break	3:00-3:15 Break	
	3:15-5:00 **Workshop Discussion Teams** **Berkner Room Breakouts** Teams 1-2 Identification of Psychological Stressors & Mitigation Strategies Teams 3-4 Functions/Tasks and Volume Drivers Identification	3:15-4:30 **Workshop Discussion Teams** **Berkner Room Breakouts** Development of advisories of human factors consequences of non-conforming to the parameters	
4:30 **Tour Of JSC Buildings 220 And 7** Habitat Demonstration Unit 20' Chamber	5:00-05:30 **Briefing to Workshop by Discussion Teams** Summary Of Stressors/ Mitigation Strategies and Volume Drivers	4:30-5:30 **Wrap up**	
	05:30 **Conclusion of Day 2**	5:30 **Conclusion of Day 3**	
6:00 **Conclusion of Day 1**	06:30 **Group Dinner in Kemah** (optional to participants)		

Appendix D:

Full Matrix of Stressors, Design Mitigations and Research Recommendations

Psychological Stressor Category	Design-Driving Psych Stressor	Details	Citation/Reference	Habitat Layout Guidance
Allocation of Space (H)		**This category deals with the allocation and positioning of certain types of volume to meet psychological needs of the crew.**		
	Lack of Personal Space / Lack of Private Space	Private and personal space were both identified as highly important to the psychological well being of crew, providing a retreat from social stressors, separation from work areas, a place to interact with family members, and providing a location for personal items.	"A sense of privacy as well as a need for personal space becomes more important over longer durations." - HIDH p555; "ensure privacy of personal communications... (electronically as well as) from private quarters" - Stuster (1996), p211; "Antarctic experts recommend that provisions should be made to permit isolated and confined personnel opportunities to get away from their fellow crew members" Stuster (1996), p. 274; Having private crew quarters in which a crew member can be alone thus becomes extremely important on long-duration missions (Santy, 1983; Kanas and Manzey, 2008, as cited in Slack et al., 2008). NASA-STD-3001, V2 7071	- Provide individual, separate sleeping/personal quarters w/auditory isolation (mandatory) and physical separation (if possible) for each crew member - Isolated locations throughout the vehicle - Separation of private spaces from spaces allocated for common, social areas and congested translation paths is preferred - Visual separation of private spaces from each other to allow for perception of increased privacy - Rotating shifts

Psychological Stressor Category	Design-Driving Psych Stressor	Forward Work/Research	Analog
Allocation of Space (H)			
	Lack of Personal Space / Lack of Private Space	- Noise abatement - Volume acceptability testing of private crew quarters - Airflow, velocity, temperature of air conditioning system in crew quarters	ISS; Antarctica. McMurdo specifically offers remote, long duration missions in sensory deprived environment, with private sleep quarters.
		- Assess "perceived" personal space and privacy under different layouts	Simulations of long duration missions (such as the 500 day study or long duration stays at HDU), ideally where living quarters can be reconfigured.
		- Assess "perceived" personal space and privacy under different layouts	Simulations of long duration missions (such as the 500 day study or long duration stays at HDU), ideally where living quarters can be reconfigured. Assess sociometrics at McMurdo and on ISS (where private quarters and common areas are provided).
		- Assess "perceived" personal space and privacy under different layouts	Simulations
		- Assess "perceived" personal space and privacy under different layouts	

Psychological Stressor Category	Design-Driving Psych Stressor	Details	Citation/Reference	Habitat Layout Guidance
Allocation **of Space (H)**	Feeling of "Crowdedness"	The perceived volume is adversely affected by the increased number of crew "traffic interactions" (which can include the displacement of one crew member to allow for translation of others, or desired simultaneous use of equipment and workstations). Leads to a feeling of inadequacy of the size or layout of the habitat. This stressor can be mitigated by either implementing layout changes or adjusting schedule to reduce forced crew interaction/displacement.	HIDH p572, NASA-STD-3001, V2 Section 5	- Separation of high traffic functions - Appropriate task scheduling/ task location - Dedicated translation paths in integrated environment - Increased volume or other dimensions to increased actual/perceived space - Rotating shifts
	Lack of Privacy of Waste & Hygiene Compartment	Increased privacy of highly personal activities such as crew waste collection and hygiene, contributes to a decrease in intra-crew conflict which could lead to decreased performance.	HIDH p501, 503; "Certain personal activities such as sleeping, personal hygiene, waste management, and personnel interactions require some degree of privacy. Private areas where these activities occur should not be placed in passageways or highly congested activity centers." - HIDH p577; NASA-STD-3001, V2 7017	- Dedicated, private area for waste and hygiene with hygiene areas away from dining area and medical station - Separation of WHC area from translation area3s

Psychological Stressor Category	Design-Driving Psych Stressor	Forward Work/Research	Analog
Allocation **of Space (H)**	Feeling of "Crowdedness"	- Clear definition of operations assumed during mission with detailed schedule could allow for analyses to layout interiors with significantly reduced crew congestion or crew displacement. -Development of scheduling tools that incorporate layout considerations; testing of these scheduling tools	ISS, Ground Simulations
	Lack of Privacy of Waste & Hygiene Compartment	- Could potentially determine actual volume # - Determination of # of bathrooms (presumably based on crew size)	ISS, Ground Simulations

Psychological Stressor Category	Design-Driving Psych Stressor	Details	Citation/Reference	Habitat Layout Guidance
Workspace (H, L)		**This category addresses the space allocated and workstations designed for meaningful work and activities needed for the psychological health of the crew.**		
	Lack of Meaningful Work/Activity	A lack of meaningful work/activity during a long duration mission can lead to increased psychological and psychosocial stress, resulting in performance decrements and depression/frustration.	Stuster (1996); Stuster (2010); Palinkas (2007); Manzey (2004)	- Provide individual development plans for each person's work goals, progress, and achivements
				- Allocation of space and resources to accommodate each individual's work and activities (i.e. science, laboratory equipment, electronic curriculum, etc...). Each individual should have their own workspace and materials should be appropriately placed for ease of use and improved functionality
				- Volume will be needed to hold samples and toolkits for in-flight experiments. Other features to impact volume may include electronic equipment to store data (workstations and hard drives) and a telescope. Equipment needed for analysis of collected samples during inbound flight.
	Sense of Poorly Placed Stowage	Poorly placed stowage for performance of tasks can contribute to frustration or other forms of psychological stress		- Ensure stowage types are near designated areas (i.e. food near dining)
				- Ensure that not all materials are stowed in one place

Psychological Stressor Category	Design-Driving Psych Stressor	Forward Work/Research	Analog
Workspace (H, L)			
	Lack of Meaningful Work/Activity	- Determination of the appropriate level of crew autonomy and selection of tasks for greater crewmember satisfaction	HDU, Antarctica station, NEEMO, ISS, etc.
		- Need list of activities to be performed on long duration missions to inform designers of necessary equipment, crew composition, and scheduling requirements - Develop individualized goals for each crewmember to ensure meaningful activities	HDU/Simulation; Antarctica station to test behavioral outcomes; ISS
		- Systematically assess current NASA processes for providing crew members with hardware and electronic resources. How are these ensured to fit within specific parameters?	Data Mining
	Sense of Poorly Placed Stowage	- Leverage ISS experience with stowage and consider placement for function and performance early in designs	ISS

Psychological Stressor Category	Design-Driving Psych Stressor	Details	Citation/Reference	Habitat Layout Guidance
General and individual control of environment (L)		**Control over lighting, airflow,**		
	Lack of Individual Controls Over Temperature, Ventilation or Lighting	Particularly in crew quarters, anecdotes indicated that insufficient levels of control over personal environment, particularly during sleep, can lead to poor sleep and the associated psychological stressors.	There are many possibilities for using interior lighting to improve habitat aesthetics (Illuminating Engineering Society as cited by Stuster, 1996); Lack of local control of lighting sometimes interfered with scheduled activities on Skylab (Johnston, 1975, as cited in Stuster, 1996).	- Place individual controls and distribution vents in crew quarters and at workstations
	Lack of Reconfigurability for Cultural Difference / Personal Space Preferences	Customize-ability and reconfiguration to best suit needs of the crew can significantly decrease frustration at inflexible spaces.	HIDH p574	- Reconfigurable packaging for crew accommodations and furniture - Modular design with multiple applicable locations for multiple activities

Psychological Stressor Category	Design-Driving Psych Stressor	Forward Work/Research	Analog
General and individual control of environment (L)			
	Lack of Individual Controls Over Temperature, Ventilation or Lighting	ISS - record use of individual controls of lighting and comments which would lead to expansion of the ranges of control or improvements to current crew quarters design	ISS
	Lack of Reconfigurability for Cultural Difference / Personal Space Preferences	- Survey of ISS and other astronauts concerning desire for reconfigurability of outfitting - Usability testing of various reconfigurable outfitting designs - Simulations; Antarctica stations and HDU - Microgravity testing of down selected outfitting at ISS	Antarctica
		- Simulations; Antarctica stations	

Psychological Stressor Category	Design-Driving Psych Stressor	Details	Citation/Reference	Habitat Layout Guidance
Systems to address sensory monotony (L to M)		**Space and resources should be provided to stimulate cognitive, visual, auditory, tactile, gustatory, olfactory, motor, etc.** **(L to M - area for plant growth)**		**1. greenhouse to grow herbs, 2. window with camera and telescope or projections of space, 3. individualized virtual window, 4. 'holodeck', 5. walls or surfaces with varied textures and colors**
	Lack of Stimulation/Sensory Variability	Current missions to the ISS provide a window with a close view of earth, real time communication with loved ones at home, and crew care packages that bring novel items (i.e. fresh fruit) to astronauts throughout the duration of their six month stay. Future long duration missions will not have these countermeasures as a way to mitigate sensory deprivation. Evidence shows that cognitive, visual, auditory, tactile, gustatory, olfactory, motor monotony, as experienced in isolated, confined, and extreme environments, can serve as a chronic stressor to the individual. Also, long term lack of choice and control over work format and leisure can negatively impact mood - this impacts on volume as choice and control necessitate a minimum amount of variety.	Gunderson (1963); Suedfeld and Steel (2000); Otto (2005) and Salam (2009)	- Windows (Provide visual stimulation of high quality close to Earth, but limited utility on long duration transit missions)
				- Virtual Windows - Camera with projections of space, video of terrestrial footage, telescope,
				- "Holodeck" or other virtually immersive environment
				- Increased spatial vista within habitat
			Evidence of neurobehavioral effects of light. Light is one of those stimuli of which we are not consciously aware of all of its effects. (Salam 2011, in print. This is subjective, not based on hard data so probably other reference needed)	- Lighting, colors, and other visual countermeasures to increase sensory stimulation
				- Greenhouse or other introduction of plants and natural elements for tactile, visual, gustatory, olfactory
				- Different surfaces in the interior to maintain tactile senses
				- Provision of musical instruments and music selection to counteract auditory
				- Enhance exercise system to include virtual experience
				- Allocation of space for exercise equipment and "stretch-out" room

Psychological Stressor Category	Design-Driving Psych Stressor	Forward Work/Research	Analog
Systems to address sensory monotony (L to M)			
	Lack of Stimulation/Sensory Variability	- Data mining; assess effects on behavioral outcomes	Antarctica- Concordia Station
		- Deploy in remote, long duration environments; compare behavioral health outcomes	Antarctica, Submarines
		- Development and testing in long duration environments, i.e.. Antarctica	Antarctica
		- Study to characterize the impact of spatial vista on psychological acceptability	All
		- Development of systems for spaceflight	Antarctica, Submarines, ISS
		- Determine to what extent plants address these sensory systems so can develop other CM if these are not sufficient	Antarctica, Submarines, ISS
			Antarctica, Submarines
		- Interview flyers, others in LDM to identify what works/doesn't work about this and other recreational CM	Antarctica, Submarines, ISS
		- Development of systems for spaceflight	Antarctica, Submarines, ISS

Psychological Stressor Category	Design-Driving Psych Stressor	Details	Citation/Reference	Habitat Layout Guidance
Systems to address social monotony (L)		**Resources should be provided to facilitate communication with family and friends**		
	Social Deprivation / Lack of Common Areas	Lack of group spaces to encourage group activities can result in decreased crew cohesion		- A common area for recreation, large enough to accommodate all crew members inside at the same time
				- Include 'television' (or equivalent) for crew to watch movies together (movies in the form of data can be transmitted from earth to also provide sensory stimulation)
				- A common area for dining, large enough to accommodate all crew members dining inside at the same time. This can be the same as the common area for recreation (converted). Kitchen required for food
	Limited Communication with Home	Communication system with family and friends at home		- Communication system should be provided in each private quarter
				- System that facilitates voice and text should be provided
				- Space for a "holodeck" to provide visual and auditory connection with loved ones at home.
				- Private space with pictures of family members

Psychological Stressor Category	Design-Driving Psych Stressor	Forward Work/Research	Analog
Systems to address social monotony (L)			
	Social Deprivation / Lack of Common Areas	- Comparison of crew interactions in habitats with variations of group spaces	Simulations; small team in long duration analogs such as Concordia?
	Limited Communication with Home		
		- Development of systems for spaceflight	
		- Development of systems for spaceflight	

Psychological Stressor Category	Design-Driving Psych Stressor	Details	Citation/Reference	Habitat Layout Guidance
Crew composition (H)		**Number, gender, cultural differences, roles, leadership, relationship, crew selection and training**		
	Crew composition may be a cross cutting /high level driver/ overarching category which impacts several other stressors in other categories, and can be addressed via other habitat requirements. Input and suggestions are welcome here.	1) Crew number can impact crew dynamics (e.g. potentially higher risk of marginalisation and group dysfunction with 3 crew versus 4 or more) 2) The presence of female crew members amongst predominantly male crews can gave a positive influence on group dynamics - mixed crews may impact design and layout (evidence on female vs. male preferences regarding environment) 3) Crew members of differing nationalities will have different expectations and needs regarding private space, leisure etc	1) Palinkas (he spoke in depth about this at the workshop so assume evidence exists) 2) Rosnet et al (Mixed-gender groups: coping strategies and factors of psychological adaptation in a polar environment. Aviat Space Environ Med. 2004 Jul;75(7 Suppl):C10-3.)	- Characteristics of the crew (team size, gender makeup, job roles, cultural backgrounds) which are established prior to the mission and will not change as a result of the mission should be considered when defining the habitat requirements.
Physiological and Medical Issues (M)		**Includes waste management**		
	Lack of Hygiene Separation	Separation of dirty-clean areas has a psychological component beyond the functional requirement separating these areas.	HIDH p574	- Provide separation between clean areas (medical treatment, food prep, crew quarters, etc.) and dirty areas (hygiene, dusty areas, etc.) Medical treatment area may need to be separate as a biological contaminant (dirty) and a sterile (clean) area. - Provide olfactory or other partitions to prevent contamination of clean areas. This can include closed, separately ventilated areas.

Psychological Stressor Category	Design-Driving Psych Stressor	Forward Work/Research	Analog
Crew composition (H)			
	Crew composition may be a cross cutting /high level driver/ overarching category which impacts several other stressors in other categories, and can be addressed via other habitat requirements. Input and suggestions are welcome here.	- Data mining (data and anecdotal evidence from space flight and other international agencies) to determine things such as: - if married, then configuration shall ____ - if two males and two females, then configuration shall______ - if three crew then configurations shall ____	Forward work should include chamber studies that evaluate team dynamics under long duration missions in confinement. Cultural issues should also be considered. Crew composition is also a driver in Con Ops - task definition, meaningful work, etc. Presumably any missions to near-Earth asteroids or Mars will be international collaborations - therefore cultural differences and needs should be taken in account early in design - ? Liaise with international space agencies
Physiological and Medical Issues (M)			
	Lack of Hygiene Separation	- Implement on future layouts	

Psychological Stressor Category	Design-Driving Psych Stressor	Details	Citation/Reference	Habitat Layout Guidance
Contingency readiness (M)				
	Lack of "Backup Plan" / "Rescue Scenario"	Long duration isolation in extreme environments places severe stress on individuals which is magnified by the perception that certain contingencies have been overlooked. This "no escape" perception can be alleviated by providing backup contingencies for every scenario, including loss of a module.	Suedfeld (1991. Groups in isolation and confinement: environments and experiences. In: A. A. Harrison, Y.A. Clearwater, and C.P. McKay, eds . From Antarctica to Outer Space. New York: Springer-Verlag) Sandal et al (1996. Psychological reactions during polar expeditions and isolation in hyperbaric chambers. Aviation, Space, and Environmental Medicine. 67:227–234.	- Recommendation to have separate modules (recommendation for redundant ships, that are connected; two Orion vehicles with station module in the middle.)
				- Placement of hatches to allow for alternate escape routes. - Provision of radiation shelter

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13. ABSTRACT *(Maximum 200 words)*

This report documents the results of the Habitable Volume Workshop held April 18–21, 2011, in Houston, TX, at the Center for Advanced Space Studies, Universities Space Research Association. The workshop, convened by NASA, examined factors that feed into understanding minimum habitable volume requirements for long-duration space missions. While confinement studies and analogs have provided the basis for the guidance found in current habitability standards, determining adequacy of the volume for future long-duration exploration missions is more complicated. An improved understanding of the relationship between behavioral and psychosocial stressors, available habitable and net habitable volume, and interior layouts was needed to judge adequacy of long-duration habitat designs. A multi-disciplinary group of experts from the medical and behavioral sciences, spaceflight, human habitability disciplines, and design professionals identified the most salient design-related stressors anticipated for a long-duration exploration mission. The stressors were organized into eight major categories: allocation of space; workspace; general and individual control of environment; sensory deprivation; social monotony; crew composition; physical and medical issues; and contingency readiness. Mitigation strategies for the identified stressors and their subsequent impact to habitat design were identified. Recommendations for future research to address the stressors and mitigating design impacts are presented.

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