Team Health and Performance in Spaceflight Habitats

Risks, Countermeasures, and Research Recommendations

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August 2016
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Abstract

Incompatible spaceflight habitat design is a significant risk to team health and performance in long-duration missions, yet we lack sufficient data regarding the nature of that risk and how best to mitigate it. This study begins to address those knowledge gaps through a review of relevant evidence regarding risks and countermeasures and an operational assessment providing additional insights from subject matter experts, including space and analog crew members. Based on these data sources, promising countermeasures are identified and recommendations and priorities for future research are provided.
Executive Summary

Incompatible vehicle and habitat design has been identified by the NASA Human Research Program as a significant risk to team health and performance (Whitmore et al., 2013); however, there are significant gaps in our knowledge related to the nature of that risk and to the countermeasures that can help reduce it.

This study begins to address these gaps by:

1. Reviewing evidence for risks and countermeasures in order to paint a picture of our current understanding
2. Highlighting promising countermeasures for maintaining team health and performance in long-duration spaceflight and discussing the implications of these countermeasures for net habitable volume (NHV) requirements
3. Identifying important themes for further research

Three sources of data were used for the study, including:

1. An evidence review based on studies conducted in spaceflight and analogs as well as relevant literature from a range of fields including environmental psychology, environmental sociology, and architecture
2. Anecdotal data based on a targeted keyword search of the ISS crew comments database
3. An operational assessment consisting of interviews conducted with nine subject matter experts, including analog and spaceflight participants

Summary of Results

Risks. A synthesis of data from the three sources above points to a number of significant habitat-related risks to team health and performance in long-duration spaceflight. These include:

- inadequate privacy
- inadequate social space
- inadequate habitat flexibility/reconfigurability
- crowding
- incompatible layout
- inadequate stowage system
- excessive background noise
- insufficient NHV
- inadequate workspace/s
- inadequate lighting
- miscommunication
- reduced team coordination

Evidence shows that these environmental risks can have profound negative impacts on team health and performance, including intergroup friction, loss of team cohesion, social withdrawal, reduced supporting behavior, mental fatigue, increased performance errors, reduced productivity, miscommunication, and reduced team coordination.
Countermeasures. The evidence review and operational assessment identified a number of countermeasures for maintaining team health and performance. All are potentially important, but the ones identified as likely being the most powerful – that will provide the biggest bang for the buck – are listed in bold.

- Private crew quarters
- Team/social room
- Habitat flexibility/reconfigurability
- Efficient and organized stowage system
- Adequate/flexible workspace
- Design to increase perceptions of volume (e.g., long sight-lines, use of color, windows)
- Efficient translation paths and separation of incompatible activities
- Noise reduction
- Adequate/flexible lighting
- Horizontal (vs can-shaped) vehicle
- Crew scheduling, training, and selection with habitat in mind

Recommendations

Research Recommendations. The research recommendations and priorities provided in this report are a function of our current understanding of the largest risk factors and most promising countermeasures in the long-duration spaceflight context and of the most significant knowledge gaps. The highest priority research areas are:

- **Private crew quarters.** Private crew quarters provide team members with a place to escape social interactions and recharge and will be a critical countermeasure for maintaining team health and performance in long-duration missions. More data are needed on minimum acceptable volume, including an understanding of how best design practices might reduce volume requirements.
- **Habitat reconfigurability/adaptability.** Design-based research is needed to develop and test approaches and technologies for adaptable habitat interiors to meet both short- and long-term changes in needs and preferences.
- **Stowage systems.** Design-based research is needed on developing and testing efficient and adaptable stowage systems, including both hardware and software (scheduling and inventory tracking) aspects of stowage, so that stowage supports and facilitates, rather than impedes, team performance.
- **Team-based NHV requirements.** Although there has been considerable work done on estimating volume envelope requirements for individual crew members, more research is needed to determine volume requirements for team tasks and activities. This will help inform NHV requirements for separate activity zones and for the overall habitat.
Operational Recommendations. Operational recommendations are based on strong existing countermeasure support and high applicability to current spaceflight operations (not solely to long-duration spaceflight). Operational recommendations include:

- Schedule tasks to minimize crowding and maximize separation of incompatible activities.
- Maximize efficiency of current stowage systems and schedule stowage-related activities appropriately (i.e., allowing ample time for unstow/stow).
- Bolster training related to team health and habitability.
- Collect data on team and habit factors in current operations. Further recommendations are made for collecting data through the modification of existing tools, namely crew debrief interviews and the Space Habitability Observation Reporting Tool (iSHORT) questionnaire.

Visual Overview of the Study
For the reader wanting a quick visual tour of this project, please refer to the diagrams and tables in the following order:

1. Table 1 (page 2) shows the HRP-identified knowledge areas and gaps that the study addresses.
2. Figure 1 (page 1) depicts the general study methods.
3. Figure 2 (page 36) depicts the major identified team risk factors in long-duration spaceflight related to incompatible habitat.
4. Figure 3 (page 38) depicts the identified promising countermeasures for reducing risk factors.
5. Table 2 (page 45) shows the research recommendations and priorities for each risk factor.
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Introduction

The ability of a spaceflight crew to get along, sustain motivation and morale, and maintain a high level of performance over the duration of the mission is a critical component for the success of any manned spaceflight mission. Yet despite astronauts being some of the most capable and productive people on (or off) Earth, risks to team health and performance abound. Some of these risks are a function of psychological and sociocultural factors – for example, inadequate cooperation, coordination, communication and psychosocial adaptation within a team (Schmidt et al., 2009). But some of the risks are a function of the spaceflight environment itself as isolation, confinement, monotony, crowding, lack of privacy, noise, inadequate lighting, and other environmental stressors take their toll. And the more time one spends in the environment, the more serious the risks become.

Although incompatible vehicle and habitat design is a recognized risk factor for team health and performance in long-duration spaceflight (Whitmore et al., 2013), specific risks and countermeasures to ameliorate these risks are understudied and there is still much we do not know (Mohanty et al., 2006; NASA HRP, 2015). The study reported on here (Figure 1) begins to address some of these knowledge gaps. Specifically, it addresses risks identified by the Human Research Program (HRP) from two different Elements – Behavioral Health and Performance (BHP) and Space Human Factors and Habitability (NASA HRP, 2015). These risks and associated identified knowledge gaps are shown in Table 1.

This study lays the groundwork for future research by exploring and synthesizing data from a number of different sources to: identify major environmental risk factors for team health, highlight potential habitat-based countermeasures for maintaining team health (including a discussion of implications for net habitable volume), and identify important themes for further research and for current operations. The data sources include:

![Figure 1. Study design, showing the three data sources informing research recommendations.](Image)
1. An evidence review based on studies conducted in spaceflight and analogs as well as relevant literature from a range of fields including environmental psychology, environmental sociology, and architecture.
2. Anecdotal evidence based on a targeted keywords search of the International Space Station (ISS) crew comments database.
3. An operational assessment based on interviews conducted with nine subject matter experts (SMEs), including analog and spaceflight participants.

Table 1. Elements, Risks, and Gaps in the HRP Integrated Research Plan Related to Habitat and Team Health and Performance.

<table>
<thead>
<tr>
<th>Element</th>
<th>Risk</th>
<th>Gaps</th>
</tr>
</thead>
<tbody>
<tr>
<td>Behavioral Health and Performance (BHP)</td>
<td>Risk of Performance and Behavioral Health Decrements Due to Inadequate Cooperation, Coordination, Communication, and Psychosocial Adaptation within a Team</td>
<td>Team Gap 1: We need to understand the key threats, indicators, and evolution of the team throughout its life cycle for autonomous, long-duration and/or distance exploration missions.</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Team Gap 3: We need to identify a set of countermeasures to support team function for all phases of autonomous, long-duration and/or distance exploration missions.</td>
</tr>
<tr>
<td>Space Human Factors and Habitability (SHFH)</td>
<td>Risk of an Incompatible Vehicle/Habitat Design</td>
<td>HAB-01: We need to understand how new aspects of the natural and induced environment (e.g., vehicle/habitat architecture, acoustics, vibration, lighting) may impact performance and need to be accommodated in internal vehicle/habitat design.</td>
</tr>
<tr>
<td></td>
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<td>HAB-03: We need design guidelines for acceptable net habitable volume and internal vehicle/habitat design configurations for predetermined mission attributes.</td>
</tr>
<tr>
<td></td>
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<td>HAB-05: We need to identify technologies, tools, and methods for data collection, modeling, and analysis that are appropriate for design and assessment of vehicles/habitats (e.g., net habitable volume, layout, and usage) for predetermined mission attributes, and for refinement and validation of level of acceptable risk.</td>
</tr>
</tbody>
</table>
Effects of the Physical Environment on Team Health and Performance: A Review of the Evidence

From a social and team perspective, a human-compatible environment is one that offers social support, offers opportunities for meaningful participation in social activity, is predictable, is conducive to both solitary activity and productive group interaction, enables the management of social interactions by supporting freedom of movement between one social phase and another (e.g., privacy and group interaction), and limits environmental distractions such as noise, inadequate lighting, and uncomfortable temperatures (Boyden, 1971; Heerwagen, 1998; Kaplan and Kaplan, 1982).

When the environment fails in one of these aspects, not only are there negative consequences in terms of individual well-being, but also in terms of increased social dysfunction and decreased team performance. When the environment is one in which people spend an extended period of time and from which there is no option of evacuation, the risk of negative effects is amplified.

Although relatively little research exists on team dynamics and performance specifically in spaceflight environments, significant findings from the broader literature (from spaceflight analogs as well as from literature on workplace and residential design, social interactions, and team performance) provide insights on environmental risk factors in space habitats and how these risks might be reduced through environmental design. A review of the evidence identified a number of relevant risks. These are discussed in detail below, and include those related to: crowding, lack of privacy and personal space, inadequate support/areas for team activities, inadequate work environment/s, and other incompatible environmental characteristics such as noise and lighting.

Where available, evidence for impacts specific to team performance is highlighted, although much of the literature deals more generally with environmental impacts on team relationships and social interactions. Because astronauts live and work together, all relevant studies were reviewed and synthesized, with the assumption that in a long-duration group living environment work and life are inextricably intertwined, with team relationships and team performance affecting one another, and it is thus not particularly useful to consider these different aspects of team health in isolation.

Crowding

Despite the social isolation and relatively small teams in spaceflight, the environment may feel crowded because the small confined quarters and the nature of the work demand constant social interaction with few opportunities for privacy (Simon et al., 2011). Feeling crowded is not just a nuisance; it can also be a major source of stress and has been associated with a host of negative outcomes in both short- and long-duration (i.e., multi-year) studies.
Studies have shown that crowding can negatively impact social interactions, decrease cognitive and physical performance, and cause stress and mental fatigue (Ashcraft and Scheflen, 1976; Hickson and Stacks, 1985; Raybeck, 1991; DeBeer-Keston et al., 1986; Harrison and Connors, 1984). In addition, there is some evidence for lack of habituation to crowding. One laboratory study on the behavioral, physiological, and psychological effects of crowding, for example, showed similar effects of crowding during each of three crowding exposures over a 3-week period; in other words, crowding effects were not reduced through repeated exposure to, familiarity with, or expectation of the crowded condition (Epstein et al., 2006). On the contrary, the negative impacts of crowding seem likely to increase over time (Zeedyk-Ryan and Smith, 1983; Harrison and Connors, 1984).

**What is crowding?** While density is an objective measure of the number of people in a limited space, crowding is a subjective experience of psychological stress due to a higher-than-desired concentration of people in a particular setting. The perception of crowding is influenced by a variety of factors, with an increased experience of crowding a function of decreased perceived physical size of space, increased number of social interactions (social density), decreased perceived control over these interactions, inability to leave the environment, increased amount of time spent in the environment, violations of personal space, and task or goal impediments due to other people (Insen and Lindgren, 1978; Altman, 1975; Baum and Epstein, 1978; Evans and Wener, 2007; Raybeck, 1991; Paulus, 1972; Sundstrom, 1986).

**Crowding and social interaction.** When people cannot escape from or avoid social interactions, a common response is social withdrawal. Evans and Lepore (1993), for example, demonstrated that college students living (for approximately 8 months) in higher-density apartments were less likely, as compared to those living in lower-density apartments, to seek and give social support in stressful situations and tended to perceive people outside the apartment as less supportive. Follow-up studies (Evans et al., 2000) showed that the coping strategy of social withdrawal in response to chronic crowding is related to changes in social information processing: those spending more time in crowded conditions are less likely to pick up on social cues even under uncrowded conditions.

Responding to confined living with social withdrawal has also been shown to be a potential problem in space analogs. Studies of both American and Italian Antarctic winter-over crews, for example, showed a significant decline over time in the extent to which crew members both asked for and provided help and advice to one another (Palinkas, 2000; Peri et al., 2000). From a psychological perspective, it has been argued that this withdrawal is an effective coping mechanism for regulating social interaction and for reducing the stress associated with crowding (Evans et al., 1996 and 2000; Raybeck, 1991) – the equivalent of avoiding eye contact in a crowded elevator. From a team perspective, however, social withdrawal can have
damaging effects, reducing overall team well-being and impacting performance. Palinkas (2000), for example, noted several cases of Antarctic winter-over crew members socially withdrawing (temporally or spatially), and thus becoming both ostracized and unavailable for team efforts.

The negative social effects of crowding appear to be cross-cultural even though expectations of density may vary. Lepore et al. (1991) undertook a cross-sectional study of males in India (from three different castes and with an average of 8 years in their current residence) along with a longitudinal study (over approximately 8 months) of American college students. They found that across all populations, residents of higher-density dwellings showed more signs of psychological stress and that this was mediated by an increased susceptibility to the negative impacts of everyday social hassles. A follow-up study (Lepore et al., 1992) suggest that these results can be explained by a reduced ability for residents of high-density homes to avoid or escape common social hassles such as arguments.

**Crowding and performance.** Studies show that crowding is associated with decrements in performance of complex cognitive tasks, but generally not of simple tasks that require little attention. These effects appear to occur both in the short term (e.g., in laboratory studies) and over longer time spans (Saegert et al., 1976; Sinha and Sinha, 1991). Several studies, for example, have shown that college students living in high-density dorm rooms have significantly lower grades over the course of their residence than those living in lower-density rooms (Glassman et al. 1978; Karlin et al., 1978). Follow up studies (Karlin et al., 1979) show that once students in high-density residences are relocated to less crowded conditions (for example, in their sophomore year), their academic scores improved. Notably, the students in these studies were randomly assigned to the different density conditions, constituting a natural experiment. Studies such as this address one of the major criticisms of crowding studies: namely that the populations in crowded conditions may well be more susceptible to crowding effects because of their lower socioeconomic level or other uncontrolled variable.

In addition to negatively impacting cognitive tasks, crowding can also impact physical performance, largely due to the presence of physical impediments and constraints. One study of the effects of crowding on physical and mental performance asked participants under varying levels of crowding to locate products on supermarket shelves and make somewhat complex price comparisons among products (Bruins and Barber, 2000). Increased crowding was correlated with both decreased physical performance (locating items) and decreased mental performance (comparing prices), although crowding led to a more rapid decline in cognitive performance than in physical performance.

The most widely accepted explanation for the effects of crowding on cognitive performance is that of mental overload (Langer and Saegert, 1977; Saegert, 1978; Bruins and Barber, 2000):
Simply put, the more that is going on in the environment (including extraneous social interactions and visual and auditory information that are not relevant to the task at hand), the more information there is to process and filter in order to focus on what’s important. If one is forced to operate in informationally noisy environments for extended periods of time, the result is mental fatigue.

Mental fatigue clearly has negative impacts on individual psychological health and performance, including decreased ability to focus, reductions in executive functioning, and impaired performance across a range of tasks (Kaplan and Kaplan, 1989; Lezak, 1991; Cimprich and Ronis, 2003; Tennesen and Cimprich, 1995). In the spaceflight context, however, the social consequences of mental fatigue may be even more significant. Individuals suffering from mental fatigue have been shown to be less able to inhibit responses, less patient with and tolerant of others, and more prone to say negative things, act in inappropriate ways, and engage in risky and violent behaviors (Kuo and Sullivan, 2001; Kaplan and Kaplan, 1989; Jonides et al., 2008; Lezak, 1991). At the low end of risk, mental fatigue could lead to impaired team cohesion— for example, increasing annoyance at another crew member’s quirks or lashing out at other crew members or at ground control due to fatigue (Stuster, 2010). At the high end of risk, increased impulsivity and group conflict could be disastrous.

**Extrapolation of crowding research to long-duration spaceflight.** Taken as a whole, the studies reviewed here provide strong evidence that crowding has significant negative effects on individual psychological health, social functioning, and both behavioral and mental performance. Furthermore, there is evidence that these effects are found both in the short term and over longer time periods, do not diminish over time (on the contrary, effects mediated by mental fatigue would likely increase over time), and are found across a wide range of cultures and populations.

Is crowding research applicable to the astronaut population? Certainly astronauts are different in many respects from the populations typically used in crowding research. Furthermore, astronauts are trained to expect crowded conditions and indeed, the ability to successfully function in crowded environments (e.g., an analog environment) may have been a factor in their selection as some space agencies such as the Japan Aerospace Exploration Agency (JAXA) use analog stays during the selection process. Yet we have no reason to assume that these differences make astronauts less susceptible to the negative effects of crowding. Although crowding does not emerge as a significant issue in studies of spaceflight habitability, current spaceflight and analog habitats are not of high enough fidelity to provide insight into how astronauts might respond to the level and duration of crowding expected in a long-duration/long distance mission. Most analog and space missions with high social density (e.g., NASA Extreme Environment Mission Operations (NEEMO) and the Space Shuttle) are of very
short duration and the habitats associated with longer-duration missions (e.g., Antarctic research stations, Mars-500 research analog, the ISS) are spacious compared to what one would experience in a long-duration/long distance mission such as a mission to Mars or near-Earth asteroid. In short, there is no reason to assume that astronauts are immune to the effects of crowding or that they can be inoculated against the effects of crowding, and we must therefore assume that crowding is a significant risk factor in long-duration spaceflight.

The nature of space habitats and other isolated, confined and extreme (ICE) environments, in fact, make them particularly likely to instill feelings of crowdedness. In laboratory settings, for example, subjects under ICE conditions reported significantly more stress due to crowding than subjects exposed to the same density but in a non-ICE context (Evans et al., 1988). Feelings of crowdedness in space habitats may also be increased by the number of times crew members are displaced to allow others to pass, or the extent to which there is competition for equipment or workstations (Simon et al., 2011).

The impacts of crowding in space habitats might include both decrements in physical performance (e.g., as work on tasks is impeded by the transit of other crew members in close quarters or by competition for tools and other resources) and cognitive performance (e.g., due to the necessity to block out social, visual and auditory distractions associated with having others in close proximity). Furthermore, given that numerous studies of mental fatigue have shown continued and increasing performance, behavioral, and social decrements over time, we would expect the cognitive and social effects of crowding to increase over the course of a long-duration mission, particularly in the absence of countermeasures to reduce sense of crowding and provide opportunities for mental restoration.

**Architectural and design mediators of crowding.** Because sense of crowding is influenced by multiple factors, there are multiple methods for modifying it beyond simply increasing the volume of the space; these include altering the layout, providing opportunities for privacy, changing crew schedules, or employing other measures to reduce unintentional social interaction and increase perceptions of the size of the space. Environmental design, in particular, can be a powerful means of reducing sense of crowding (Evans and Lepore, 1992). There is empirical support that the following environmental features can be manipulated to impact sense of crowding.

**Control and flexibility.** Of paramount importance to sense of crowding and its associated stress is perceived control, both over one’s physical environment and over one’s social interactions (Baum et al., 1981; Hickson and Stacks, 1985; Knapp, 1978; Schmidt and Keating, 1979; Sherrod, 1974; Sommer, 1969; Proshansky et al., 1970). In a confined environment, one effective way to control interactions is by establishing and maintaining spatial and behavioral norms. In spaceflight, for example, crews may have designated quiet zones, norms for social
interaction during individual work, and norms regarding behavior patterns to maintain privacy (see Raybeck, 1991). Another way of mediating social interaction is through flexible physical design, such as the ability to modify one’s orientation with respect to others or to change a social space to accommodate diverse activities (Raybeck, 1991).

**Sub-unit size and degree of private enclosure.** Sense of crowding can be greatly reduced with the provisions of private space. Several studies in prisons, for example, have shown that independent of the overall square footage of the habitat, enclosed sleeping areas are associated with a decreased sense of crowding and a reduction in health complaints (Cox et al., 1982; Schaeffer et al., 1988). In spaceflight and space analogs, enclosed private space is just as important as it allows crew members to mediate social encounters (Aiken, 2014).

**Structural depth.** The way in which overall square footage or volume is laid out and partitioned can significantly affect sense of crowding, with increased architectural depth (number of separate spaces) associated with a reduced sense of crowding. In their study of the impact of residential depth on social withdrawal and psychological stress, Evans et al. (1996), for example, found that college residents of high-density homes with greater architectural depth (the number of spaces that one passes through in moving from one part of the residence to another) were significantly less likely to socially withdraw or be psychologically distressed than residents in high-density homes of equivalent square footage but with less residential depth. (The students had been living in their respective residences for approximately 8 months). The authors hypothesize that the effects were due to an increased ability to regulate social interaction by altering the degree of separation among oneself and others in the residences with more architectural depth.

**External views.** Distant external views can decrease sense of crowding by increasing one’s perception of the size of the space. Schiffenbauer et al. (1977), for example found that sense of crowding in high-density dormitories was lower for residents in rooms that were higher up and had broad external views than for residents in lower rooms with less expansive views. (Students had been randomly assigned to rooms and the study was conducted several months after students had been living in the residence.)

**Straight vs curved walls.** Rotton (1987) found that people were less tolerant of high-density in rooms with curved walls than in rooms with straight walls. Possibly, this was due to straight walled rooms being perceived as larger or because of an increased ability to maintain a defensible personal space (e.g., back to wall or positioning in a corner) in a straight walled room.

**Lighting and other architectural details.** Research with college students living in student residences with varying density suggests that sense of crowding is lower in brighter rooms.
(particularly those with more natural sunlight) (Schiffenbauer et al., 1977). Sound attenuation (lower levels of ambient noise) and increased proximity to open space (particularly nature areas) are also associated with decreased sense of crowding (Evans et al., 1992; Kaplan et al., 2004).

**Personal space.** Discussion of personal space needs often cite Hall’s (1959 and 1966) research on optimal interpersonal distances for facilitating different types of social interactions. According to his research, interpersonal distances of less than .5 meters facilitate intimate behaviors (e.g., comforting, threatening), distances from .5 to 1.25 meters facilitate personal conversations and relationships, distances between 1.25 and 3.5 meters are comfortable for less personal social interactions (e.g., impersonal business dealings), and greater distances are used in public settings, such as addressing a crowd.

Because Hall’s data are dated and U.S.-centric, the actual distances that he cites may not be relevant to modern times and different cultures, and thus, not relevant to a future, international mission to Mars. However, the notion that personal space is important remains relevant. Sinha and Sinha (1991), for instance, found that while social density negatively impacted performance on complex cognitive tasks among all 60 female students in India, the effect was particularly strong for students with higher personal space needs.

Personal space needs among astronaut populations have not been well-studied and no guidelines exist. But regardless of how big or small those personal space needs are, frequent and long term invasions of personal space are likely to have negative consequences for both psychological and team health.

**Privacy and Boundaries**

Intricately related to sense of crowding is degree of privacy. Private spaces can both reduce perceptions of crowding and can help mitigate the negative effects of crowding by providing a place for social escape and mental restoration. The role of private space in recovering from the stress associated with social density appears to be particularly important in ICE environments. Evans et al. (1988), for example, studied space usage over the course of a 7-month winter-over in Antarctica and found that the use of areas with visual and auditory privacy increased over time, with bedrooms used extensively to obtain privacy. Similar results have been found in laboratory studies (Altman and Haythorm, 19067; Taylor et al., 1968; Haythorn, 1973) and in shorter-duration analog studies (e.g., Mohanty et al.’s, 2006, 91-day isolation study).

The negative consequences of lack of privacy are well documented and have implications for both psychological and team health. Lack of privacy has been associated with depressed mood, decreased helpfulness, increased aggression, and a breakdown of community (Connors et al.,
In addition to individual privacy, there are also social dimensions of privacy. In spaceflight, identified social privacy needs include: (1) activity privacy (privacy of one activity from an incompatible activity), (2) dyad/small group privacy, and (3) crew privacy from outside observers (Aiken, 2014).

**Architectural and design mediators of privacy.** Privacy is not synonymous with physical isolation; rather, it is the ability to selectively control interaction between oneself and one’s group (Sundstrom, 1986; Aiken, 2014). This control is dependent on both environmental design and on behavior. Aiken (2014) found that spaceflight/analog crews develop social norms to cope with limited privacy, for example, some crews have used flags to indicate that the hygiene facility is in use or have come to a group understanding that certain areas are quiet zones. As important as these non-environmental mediators of privacy may be, however, architecture and design remain the most powerful mediators of privacy. In particular, privacy across its range of dimensions has been shown to be supported by the following:

**Private sleeping quarters.** In the context of spaceflight, it is widely agreed that personal private space – in the form of sleeping quarters – is a critical and necessary design countermeasure for reducing risk to both psychological and team health, particularly for longer-duration (over 6 months) flights (for reviews, see Aiken, 2014; Kearney, 2013; Gunderson, 1970). The ability to get away from others in order to recharge or focus on individual tasks has significant psychological benefits and, as noted above, has positive implications for team health as well.

The minimum volume required for private sleeping quarters on long-duration missions is a subject of much debate. However, a recent study of crew perceptions of privacy found strong agreement among both astronauts and analog crew members (with participants living in a range of spaceflight and analog habitats including ISS, Human Exploration Research Analog (HERA), NEEMO, Antarctic stations, chamber analogs, desert and submersible analogs) that current private space is inadequate (Aiken, 2014). A Subject Matter Expert Consensus Panel convened by NASA in 2013 to provide net habitable volume (NHV) recommendations for long-duration spaceflight also found that current private quarters on the ISS are of insufficient size for long-duration mission (Whitmire, et al., 2015). The panel recommended a volume of 5.4 m$^3$ for each individual crew quarter (as compared to current ISS crew quarters of 2.1 m$^3$). The larger volume is intended to provide some private work space as well as provide privacy and a place for restoration.
**Functional privacy.** The co-location or near location of incompatible activities can be a significant source of stress in spaceflight, and experts recommend that areas for these activities be physically (visually and acoustically) private from one another (Kearney, 2013). In particular, it is recommended that quiet and noisy areas (e.g., sleeping quarters and team room), and clean and dirty areas (e.g., galley and exercise/hygiene) be separated.

**Semi-private space for dyad/small group privacy.** Privacy is occasionally needed for conversations that do not involve the whole crew (e.g., between a leader and another crew member regarding work performance) or for small group activity. Although a dedicated semi-private space may not be feasible in the spaceflight context, spacecraft design should ensure that a suitably-sized space is available and somewhat separated from the main social hub. In a study that explored and evaluated design approaches to the ISS, for instance, researchers found that including a semi-private library/study space in a Group Activities Habitability Module was desired as a way to help relieve any social tension which might arise if off-duty crew choice were limited to communal activity in the wardroom or isolation in private quarters (Nixon, 1986). However, no module with this specific function was added to the ISS.

**Individual work privacy.** Some degree of privacy (e.g., at least privacy from visual and auditory distraction) is required to complete demanding individual tasks (which may or may not be possible to complete in private quarters). In spaceflight, where individual work/project “cubicles” are not necessarily feasible, opportunities for some privacy may be obtained through workplace design (as described below).

**Privacy of crew from outside observers.** In her interviews with astronauts and analog crew members, Aiken (2014) found that most participants wanted the ability to have some control over the indirect observation and participation of those outside the spaceflight/analog environment. These results echo Jane Poynter’s (2009) memoirs of Biosphere 2, in which she describes how an inability to escape outside observation left crew members feeling constantly on stage and was a significant source of stress. Although it is not likely that ground control would permit turning off video monitoring or other forms crew/mission surveillance, ideas should be gathered on other ways that periodic group privacy may be realized, as this is seen by crew as an important component in building team cohesion and improving relationships between crew and ground (Aiken, 2014).

**Territoriality.** Architectural features such as doorways can help to reinforce a sense of territory by denoting different functional zones and indicating the separation of public and private space (Vogler and Jørgensen, 2004). Constance Adams’ study of how crew used space during a 91-day isolation study in NASA JSC’s 20-foot chamber, for example, showed that doorways to private quarters helped differentiate public, semi-private and private space, with semi-private
conversations happening just outside or in the doorway, but with crew members never entering one another’s private quarters (Mohanty et al., 2006).

**Balance between separation and accessibility.** For optimal team functioning, an appropriate balance must be struck between individual privacy and group interaction. Thus, although the ability to remove oneself to personal private space is critical for individual and team health, measures should be in place to mitigate maladaptive social withdrawal (Sundstrom, 1986; Palinkas, 2001; Stuster, 2000). These measures could include design elements such as the arrangement and clustering of personal quarters around a semi-private space or behavior/team monitoring to alert crew and ground to tendencies toward isolation.

**Supporting Social Interaction and Team Cohesion**

Although physical proximity among crew members is, on the one hand, implicated in crowding, it can also, when intentional, facilitate social interaction and team cohesion. The importance of team co-location for collaboration and performance is discussed in the section below. Equally important is the role of team co-location in building and maintaining team cohesion. High team cohesion is associated with low levels of team conflict and high levels of team performance (Kozlowski, 2012) and many important countermeasures for supporting team cohesion (e.g., group meals, games, performances, recreation, and other group activities) require that the entire crew is able to comfortably gather in the same place (Häuplick-Muesburger et al., 2013; Moore, 1990; Simon et al., 2011). Hence, there is widespread agreement among space and analog crew, habitability experts, and other SMEs, that adequate communal space is a necessary component of spacecraft design (Kearney, 2013; Simon et al., 2011; Whitmire et al., 2015).

“Adequate space” in this context would mean a volume that permits comfortable interaction without forcing crew members to invade one another’s personal space or float/climb over one another (Simon et al., 2011; Kearney, 2013). The required volume will vary somewhat depending on the activity (e.g., watching a movie versus participating in a team building or training exercise), and multiple use scenarios would have to be considered for determining volume requirements.

NASA’s Net Habitable Volume Panel (Whitmire et al., 2015) recommended a social space that at a minimum: allows comfortable whole-group dining, food prep, and other communal activities; is flexible, for example in terms of furniture reconfiguration; includes a window to provide a focal point and to visually extend the space; and contains some point of use stowage. The figure provided for this team space, based on a crew of six, was approximately 50m³ (excluding stowage).
The location of the team room with respect to other spaces is also important to consider. A 7-month study of the spatial behavior of an Antarctic winter-over crew (Evans et al., 1988) highlights the need to locate team rooms near high traffic areas, separate them visually and aurally from private quarters and other conflicting activity areas (e.g., hygiene), and equip them with items to support socializing, such as music, food, video screen, and compatible furniture. Similar design recommendations have also been proposed by others and they received widespread support in the spaceflight community (see Moore, 1990; Kearney, 2013).

**Work Performance and the Physical Environment**

A team is a group of interdependent individuals who share responsibility for a project (or mission) outcome and the success of the team is dependent on the completion of both independent and interdependent tasks (small group and whole group). Team performance is thus a function of the ability to effectively perform both individually-focused tasks and interactive group work, and to move efficiently from one task type to the other. There is accumulating evidence that the physical environment affects performance at each of these levels (see Vischer, 2007).

**The physical environment and performance of individual tasks.** Teams are not solely defined by collaborative interactions. Indeed, to be effective team members, individuals need the time and space to be able to complete focused individual work (Heerwagen et al., 2004). In other words, they need to be able to get away, at least mentally if not physically. The benefits of being in a space that supports focused attention and minimizes distractions are many, including: increased time spent on tasks (Perlow, 1999), reduced mental fatigue (Kaplan, 2001), improved performance (Heerwagen et al., 2004), and the ability to maintain one’s cognitive “flow” (Csikzentmihalyi, 1990).

One way of reducing distraction and supporting mental focus is designing the workplace to include separate private office spaces. A number of studies have shown that office workers strongly prefer private enclosed workspaces over an open plan design (Brennan et al., 2002; Fried et al., 2001; Ornstein, 1999) and that these individual spaces are associated with decreased stress, improved co-worker relations, and increased job performance (Brennan et al., 2002).

In spaceflight, of course, private separate workspaces are rarely an option. However, there are a number of environmental attributes that can help create a sense of workspace privacy that would be possible incorporate or simulate in spaceflight habitats. Specifically, the following spatial characteristics have been shown to support effective performance of individual tasks (for a more complete review, see Heerwagen et al., 2004):
• Some degree of enclosure via, for example, workstation panels (Archea, 1977; Pedersen, 1997), particularly with a non-distracting view into a larger space (Alexander et al., 1977).
• Distance and insulation from other people and from disruptive noise (Kupritz, 1998; Fried et al., 2001, Sundstrom, 1986).
• Distance from high circulation areas (Backhouse and Drew, 1992).
• Ability to create a comfortable space in terms of environmental factors such as temperature, ventilation, etc. (Sundstrom, 1986).

In addition, window views and nature elements (e.g., plants) have been shown to have significant positive impacts on individual performance, including increasing one’s ability to focus attention (Jartig et al., 1991; Kaplan and Kaplan, 1989; Bird, 2007; Frumkin, 2001; Pretty et al., 2005; Kuo, 2004) and providing micro-restorative opportunities that can help reduce mental fatigue (Kaplan, 1995 and 2001; Clearwater and Coss, 1989). (For an in depth review on the effects of nature on psychological health and performance, see Kearney, 2013). Similarly, the presence of distant views and view corridors can contribute to a sense of privacy while allowing one to maintain a connection with the outside world (Clearwater and Coss et al., 1989).

Although the ability to reduce distractions is important for efficient and accurate performance of demanding or complex tasks, for well-learned or easy tasks some additional stimulation may be beneficial. In these instances, performing the task in a social context may actually improve performance (the so-called “social facilitation effect”, see Forsyth, 1998) by increasing alertness, motivation, and speed.

The physical environment and performance of interactive tasks. In addition to being able to effectively perform as individuals, overall team performance will depend on the ability of team members to work together and effectively communicate, collaborate, and complete interactive tasks. Many factors are important here, including team leadership, mutual respect, individual personalities, and team cohesion (Schmidt et al., 2009), but in terms of spatial facilitators of team interaction, the cornerstone is “co-presence” – that is, the sense of physically (or at least conceptually/psychologically) being together (Nova, 2003).

In its simplest sense, co-presence means that team members occupy the same space at the same time. Mutual gaze also plays an important role here because when team members are able to easily see one another, communication and collaboration are increased (Kendon, 1967; Clark and Schaeffer, 1989; Argyle and Cook, 1976).

However, creating a sense of being together requires more than spatial co-location. Of particular importance is having shared mental models in terms of problem framing, data
awareness, and other shared knowledge (for a general review of the importance of shared mental models in collaborative work, see Kearney, 2015). Team members who occupy a shared cognitive space will have better quality communication and coordination and are more likely to have better performance outcomes (DeChurch and Mesmer-Magnus, 2015). There are many factors relevant to building and maintaining shared team mental models (see DeChurch and Mesmer-Magnus, 2015, for an overview and recommendations), but in terms of designing to facilitate shared mental models in a particular collaborative task, one important aspect is the ability for team members to readily and simultaneously see relevant information displays and other artefacts (Artman, 2000; Brager et al., 2000).

One example of an effective space designed to maximize co-presence and facilitate collaboration is the “extreme collaboration” space at NASA’s Jet Propulsion Laboratory (JPL) (Chachere et al., 2003; Marks, 2002). This is an open space that was created to reduce the time to complete mission design proposals by co-locating all the necessary people and tools. Team members are highly visually and aurally accessible to one another, which facilitates rapid information sharing, an ability to monitor and quickly solve problems, and a sense of team unity. The space has been spectacularly effective – the time for design proposal completion has dropped from 3-9 months to several days (Marks, 2002; Chachere et al, 2003). However, because of the intensity of the interaction, mental fatigue among team members is commonly experienced. In the context of JPL, this resulting fatigue may be readily dissipated by a weekend of getting away and recharging. In the spaceflight context, however, where both getting away and mental restoration are difficult, the negative consequences of such fatigue would be significant (Kearney, 2013).

Other research on facilitating collaboration and team cohesion in the workplace has explored the impact that the relative placement of activity areas has on social interaction. In particular, increased positive opportunistic interaction is associated with dedicated common areas (e.g., water cooler, snack room), increased spatial visibility and translation paths that bring people in frequent proximity, particularly when there are socializing “nooks” on those paths (such as benches, plants, alcoves, windows) (Sundstrom, 1986; Heerwagen et al., 2004).

Similarly, in spaceflight design, habitability and other experts agree that interior layout is a critical factor to consider, although layout issues in space are as much about controlling unwanted interactions as they are about encouraging social interactions. Space habitats must include areas for social interaction, areas where interaction is more limited and controlled, and comfortable and logical networks of getting from one place to the other (Kearney, 2013).

**The physical environment and task switching.** In addition to being able to effectively perform individual and interactive work, overall team performance depends on the ability of individuals to readily switch from one task type to the other. Some ISS crew members have reported
difficulties in task switching, particularly in shifting from autonomous work to highly interdependent tasks (Smith-Jentsch et al., 2011). This difficulty may stem from being out of sync (temporally, emotionally, or physiologically) with other crew members and has been identified by NASA as a possible risk to team performance (NASA HRP, 2015). Proposed countermeasures for facilitating task switching have included training strategies, monitoring, and task scheduling (Stout et al., 1997; LePine et al., 2000). An additional factor to consider is the physical environment. Although little research has been done specifically on the effects of the environment on task switching, there is some relevant research on environmental contributors to attention shifting and social awareness.

Research on mental fatigue and distractions in the workplace highlights a number of environmental factors, such as noise and visual distractions, which cause individuals to orient their attention externally (Lahlou, 1999 as cited in Heerwagen et al., 2004; Heerwagen, et al., 2004). While these distractions can be detrimental to those doing complex focused individual work, they can also be manipulated to increase social awareness. Weiser and Brown (1996), for example, describe how social awareness can be increased through “back channel information” (visual, auditory, and other sensory information happening at the periphery of one’s attention), which allows workers to remain in touch with what’s going on around them. An increase in back channel information can draw one’s attention outward, away from autonomous work and toward the group.

The appropriate level of back channel information depends on the nature of one’s work and the need to be externally attuned. A high level of social awareness (such as in the JPL extreme collaboration environment) has been shown to be particularly beneficial for teams in dynamic task environments, where rapid information sharing and feedback is required, and where a high transparency of tasks is needed to support coordination (Hutchins, 2002; Marks, 2002; Cachere et al., 2003; Horgen et al., 1999). Yet, although this type of environment likely increases team syncing, or entrainment, across a range of dimensions, it is the very type of environment most at odds with focused autonomous work (Sundstrom et al., 1982; Sundstrom, 1986), and hence may impede switching from interdependent back to individual tasks.

A traditional work environment might have different areas for different tasks (e.g., private workspaces and team/conference room), and employees can facilitate task switching by physically moving from one area to the other. In the highly volume-constrained spaceflight environment, however, this is usually not possible and designing flexibility into the workspace will be important to support crew members both in completing tasks of different types and in moving from one task type to another.
Interior Design and Team Performance
Several other interior design elements have been empirically linked to team health and performance in space habitats. In particular, inadequate noise, lighting, and stowage are associated with reduced performance.

Noise. Exposure to excessive noise levels not only takes a psychological and physical toll, it can also impair performance on tasks requiring communication (for a review, see Limardo, Allen, and Danielson, 2015). An analysis of the Flight Crew Integration (FCI) ISS Crew Comments Database (Whitmore et al., 2013) shows that noise has cost the crew time during task performance by requiring translation between modules in order to be heard. Noise has also been cited as a problem even for face-to-face communication and for some crew members, excessive background noise has negatively affected their perception of ISS habitability. Noise control techniques and technology can help to mitigate performance risk due to noise. Indeed, the ISS noise exposure monitoring program suggests that since 2013 the acoustic environment on the ISS has improved due to the implementation of noise control strategies (Limardo et al., 2015).

Lighting. Adequate lighting levels and lighting attuned to maintaining healthy circadian rhythms is important not only in terms of work performance but also in terms of general health and well-being (e.g., mood and sleep cycles) (Fucci et al., 2005). Having adequate light levels in work environments is associated with higher worker productivity and worker satisfaction (Vischer, 2007; Thayer et al., 2010; Sundstrom, 1986). Appropriate lighting is particularly important over longer durations. Increased mental effort can compensate somewhat for poor lighting in the short term but as mental fatigue sets in, this becomes increasingly difficult and performance can suffer (Bluth and Helppie, 1986).

Temporal dislocation. “Free floating” or “free running,” where one crew member slips into a day-night cycle that is dramatically different from other crew members, can be a problem both for team cohesion and for team performance on long-duration missions (Guo et al., 2014; Mallis and DeRoshia, 2005; Whitmire et al., 2008) and there is strong evidence for the benefits of keeping the team temporally aligned (Simon et al., 2011). Environmental design, particularly lighting design, can help to reduce the risk of temporal dislocation by helping to maintain normal circadian rhythms (see, for example, Gooley, 2008).

Psychological Health, Team Performance, and the Environment
Environmental impacts on individual psychological health and performance in spaceflight has received considerable attention elsewhere (see Kearney, 2013 for a review) and although it is not the primary focus of this study, the impact of psychological health on team health must be noted. Psychological stress and mental fatigue not only impair individual functioning, they can impair team functioning as well, causing people to react negatively towards one another
(Sauser et al., 1978; Griffitt, 1970) and miss subtle social cues (Cohen and Lezak, 1977; Mathews and Canon, 1975; Korte et al., 1975), and leading to team tension, strained work relationships and loss of job satisfaction (Kirsh, 2000). Orasanu and her colleagues demonstrated the strength of the psychological-team health relationship in their study of the relative impact of two types of team training on team performance (reported in DeAngelis, 2008). Teams either underwent training designed to promote crew cohesion or designed to help crew members cope with stress. Results showed that the training geared toward stress reduction was significantly more successful in enhancing team performance during difficult missions than was the training focused on team cohesion.

The reverse is also true. Even positive social interactions require some level of cognitive effort (e.g., to monitor what’s being said, respond appropriately, keep track of how one looks to other group members, and withhold inappropriate responses and behaviors) and can be mentally fatiguing, leading to psychological and behavioral decrements. In the context of negative social interactions, the risks are significantly higher (Palinkas, 2000).

Given the interdependence between individual and team well-being, any countermeasures that can be put in place to maintain psychological health (again, see Kearney, 2013) will likely have a positive impact on team health (in terms of team dynamics, ability to focus on team tasks and to cope with team related problems). Likewise, any countermeasures that can be put in place to maintain team health will likely have a positive impact on individual psychological health (both by reducing the mental effort required to interact with team members and by increasing the probability that the team itself will provide positive social and psychological support).
Insights from International Space Station Crew Members: An Analysis of Crew Comments

Methods
In addition to published and otherwise available literature, the Flight Crew Integration (FCI) ISS Crew Comments Database contains useful insights on astronaut perceptions of the ISS habitat. The database contains comments from roughly 42 astronaut debrief interviews over 12 missions (expeditions 29/30 to 40/41). A portion of the debrief interview queries astronauts about habitability issues (e.g., layout) and, separately, about activities that may involve a team setting (e.g., Extra Vehicular Activities (EVAs), dining). Although the database information is anecdotal in nature and the interview does not directly ask about team health as it relates to habitability, this rich data source nevertheless provides a unique perspective related to the understudied topic of team habitability.

Because external researchers are not allowed direct access to the database, a keyword search was performed by database managers and results were then consolidated by NASA personnel to retain the integrity of the ideas while removing any raw data, including direct quotes and identifiers. Consolidated comments were then passed on to the external researcher.

The search was done within the relevant database categories (e.g., privacy, volume/topology, privacy, etc.) using the following keywords:

- Crowded, crowding
- Working together, collaboration, interdependent, helping each other, team task, team event, team training Group recreation, team recreation, group activity, team activity, socializing
- Privacy, private space, private quarters, crew quarters
- Habitable volume, layout
- Habitability
- Crew Complement/compliment, team dynamics/team work
- Getting along, team cohesion, social, team building, team growth, team bonding
- Flexible, flexibility, reconfigure, reconfigurability, modify, modifiability (this did not yield anything consistent with teams or crew interaction)

The results of the keyword search are a broad look at issues that bubbled up in ISS crew debrief interviews relevant to habitat and team health, along with some indication of the frequency with which ideas were expressed. (The themes that emerged from the keyword search also included comments not specifically relevant to habitat and team health and these were not included in the data analysis.) The frequencies with which issues were mentioned may be somewhat misleading as multiple comments on the same topic could possibly have come from
the same crew member and because crew were not specifically asked about habitat and team issues (so that an issue may have, in fact, been perceived as a problem but the astronaut did not think to bring it up).

Because of the broad brush nature of the information gathered from crew comments, an equally broad brush approach was taken to the analysis of this information. The consolidated comments were reviewed to identify relevant themes. These fell under the following categories:

- Overall Layout and NHV
- Crowding
- Private Space
- Team Space
- Stowage and Equipment
- Other Environmental Factors (Noise, Dust, Ventilation)

Each theme is discussed in more detail, below, along with a general indication of the frequency with which the theme was mentioned (using the intentionally imprecise terms of “many,” “some,” and “a few” respondents).

**Results and Discussion**

**Layout and net habitable volume.** On the positive side, many respondents perceived the overall layout of the ISS to be good, with mostly clear translation paths, and a nice variety of large and small spaces. One problem noted by many, however, was the co-location of the exercise equipment with other operations equipment, making it difficult to maneuver. Others similarly noted navigation problems in another node due to co-location issues. Likely because of the difficulties associated with co-location, many crew members noted the need for designated activity areas (e.g., lab, exercise, hygiene, and crew quarters). Maneuvering difficulties were also noted in the food prep area due to lack of space and frequent use. Likewise, several crew members noted congestion around the personal locker area because of its frequent use.

Problems related to co-location would likely be exacerbated in a long-duration vehicle because of its reduced size compared to the ISS and the associated increased need for multi-functionality of spaces. To the extent possible within these spatial limitations, it will be vital to design the habitat and schedule activities in a way that minimizes congestion and supports efficient translation.

Several crew members also noted that it took them a bit of time to adjust to navigating in a 3D space. The importance of colors and landmarks to assist with orientation was mentioned, as was the importance of handrails to facilitate movement at translation paths so that crew members do not bump into one another. Orientation and navigation aids will be increasingly
important in compact long-duration designs that maximize multi-functionality by making use of
the entire habitat volume (which would likely include a variety of orientations within that
volume).

Crowding. Overall, problems related to crowding were not mentioned with high frequency.
However, some respondents did find the galley area crowded which made movement and food
preparation difficult but did not stop them from having group meals. Some crew members also
commented on problems associated with crowding during work (e.g., planned work space was
too small due to equipment needs; space was inadequate for required activities; and scheduling
conflicts placed multiple tasks simultaneously in same space, leading to crowded conditions). A
few crew members mentioned that the ISS felt crowded when Shuttle crews were visiting; one
person noted that these crowded conditions were okay for a week but would have been a
problem for a month. Several others noted that the Shuttle itself was very crowded compared
to the ISS and that maneuvering and completing tasks in the Shuttle was sometimes difficult.

In the context of a longer-duration mission in a considerably smaller habitat, crowding will likely
become more problematic. Although crew members may feel that almost anything is tolerable
for a week or so, a 2-3 year mission is another story entirely. Based on the comments here,
particular attention should be paid to crowding in work spaces and during work activities;
crowding in these contexts are likely not only to have general negative impacts on team health,
but are also likely to directly and negatively affect team task performance.

Private space. Many crew members said the private crew quarters had adequate space and
were comfortable (although one respondent found the space too small and another noted
difficulty in donning/doffing clothing). Some crew members additionally noted the importance
of having a door on the private quarters and having the ability to decorate/personalize the
private space.

Privacy issues outside crew quarters were also mentioned. A few crew members noted the
importance of having designated private hygiene areas and others found it a negative that
hygiene often takes place in trafficked areas. Several crew members made negative comments
about being constantly on display (i.e., on camera) to the public and others noted that this
made them less efficient. A positive aspect of the on-board cameras was noted by others,
saying that video displays give the crew and the ground knowledge of where other crew
members are located, which assists in planning.

Some crew members also mentioned the importance of having dedicated “personal” spots
outside private quarters to store their things (e.g., this spot is where crew member X puts her
water bag; this other spot is where crew member Y hangs his washcloths and sweaty workout
shirts).
Although the current size of crew quarters on the ISS appear to be widely acceptable, this may not translate to a longer-duration mission. In particular, a smaller vehicle will necessarily mean less private and semi-private space outside of crew quarters (e.g., the loss of the “personal spots” mentioned above) and this may translate to a need for more space in private quarters.

**Team social space.** Many crew members mentioned the importance of social group meals, sitting together around a table, for overall group morale. Many also noted that space limitations and the separation of the US and Russian galleys made all-crew meals difficult, although they did report trying to eat together at least on the weekend if not for every dinner (several crew members, however, reported that they ate infrequently with the other agency crew). Prior to 2015 (when a large screen was installed on the ISS), some crew also mentioned the desire for a large media screen so that crew could gather and watch television and movies together.

**Stowage and equipment.** A number of problems associated with stowage were noted. Some crew members commented that the visual clutter on the ISS was fatiguing and that crowded stowage bags and compartments make it difficult to find things. Others noted that once unstowed, equipment can become difficult to manage, blocking views and contributing to a sense of crowding. Some crew members noted that having extra temporary space in some modules was very helpful for managing tools and equipment. Others noted that the co-located pantry setup helped crew to know where things were.

The risks related to stowage loom even larger on long-duration exploration missions than they do on the ISS. Because re-supply would likely not be possible, crew will be traveling with more supplies, increasing the risk of clutter and disorganization and the related impacts on sense of crowding, stress, and performance. In addition, the smaller vehicle size would limit the availability of temporary storage space. Given these realities, designing better stowage systems is of critical importance for individual and team health and performance in long-duration exploration missions.

Food stowage was also considered problematic by many crew members. Crew members noted that food sorting on orbit is an activity that is done frequently and that takes significant time and a desire for a better solution for sorting and stowing food was expressed. In the context of a long-duration mission, where there is no re-supply, food sorting may not be an issue; however, issues related to food stowage (particularly moving from longer-term to shorter-term stowage) will still need to be addressed.

In terms of work areas and equipment, flexibility was seen as important. Many crew members commented that they liked having movable work areas, equipment, and cable routes. For example, crew members used tablets for many tasks (even including video recording) because
they are portable and can be easily anchored with velcro where needed. Some crew members noted problems with using laptops in microgravity as typing and using the trackpad sometimes pushed them away. The smaller the habitat and the more multi-use the spaces within that habitat, the more important designing in flexibility will become.

**Other environmental factors: noise, dust, ventilation.** Noise was not generally mentioned as a problem although it was noted by some that earlier risers and sleep shifters had to be mindful not to disturb the other sleepers. Some crew members noted problems with dust and expressed a desire for movable cordless vacuums. Ventilation issues were also mentioned by several crew members, who noted that strong fans and vents can suck things up and that fans blowing in crew quarters can make sleeping difficult.

Although noise and other environmental factors were not perceived to be significant problems on the ISS, these factors may manifest themselves differently in different habitats and may require the implementation of different countermeasures. For example, noise may be more of a problem in a compact long-duration vehicle and that may necessitate increased noise insulation or other noise reduction strategies.
Operational Assessment

The literature on environmental risks and countermeasures related to team health and performance in long-duration spaceflight is relatively sparse. Therefore, an operational assessment was conducted to gather expert insights and opinions in order to further inform these issues.

Methods

Thirty-minute phone interviews were conducted with nine (9) SMEs. In most cases, these interviews were conducted as the first part of a 1-hour interview (the second half of the interview related to a different project and was conducted by a separate interviewer also conducting BHP-oriented research). The primary focus of these interviews was on gathering information directly from spaceflight and analog crew members and from those with direct observational and design experience (for example, habitability specialist or operations psychologist).

Participants. Participants included three women and six men representing seven different nationalities and the following areas of expertise: habitability design, flight psychology, human factors, and experience living and working in spaceflight and analog habitats (these participants had additional experience in areas such as aerospace engineering and medicine). Four participants had direct (and sometimes multiple) experience in analog environments (ranging from 2 weeks to 18 months) and 2 participants had direct, and multiple, experience in spaceflight (with missions ranging from less than 10 days to over 4 months).

Habitats. The analog and space habitats that participants had experience with (either direct or observational) include: the ISS, Mir Space Station, Skylab Space Station, Flashline Mars Arctic Research Station (FMars), Mars-500, NEEMO, Hawaii Space Exploration Analog and Simulation (HI-SEAS), the Haughton-Mars Project, and the Concordia Antarctic Research Station.

Interviews. Interviews were semi-structured, meaning that they covered specific questions but were flexible enough to pursue interesting and relevant topics that emerged during the interview. Individual interviews were based on the subset of interview questions most relevant to the SME’s area of expertise. The general interview protocol is included in Appendix A. Interview questions addressed the following:

- Aspects of the physical environment that can impede or facilitate team cohesion and performance
- Crowding (extent of problem and countermeasures)
- Team/social space
- Habitat layout effects on team health and performance
- Changes in environmental preferences and needs over time
- Environmental challenges/support for independent task performance
- Environmental challenges/support for interdependent task performance
- Environmental challenges/support for task switching
- Biggest “bang for buck” in terms of designing for team health and performance

A content analysis of interview data was performed to identify insights and opinions related to the themes outlined above. The intent of the analysis was to identify the range of perspectives and to highlight specific relevant details. Keeping in mind that the SMEs did not all respond to the same set of questions, no attempt was made to quantify responses (with the exception of the final question, which was asked of all participants).

**Results and Discussion**
At the end of each interview, the SME was asked what he or she thought were the most important aspects of spaceflight habitat design with respect to reducing risks to team health and performance. In other words, what did they feel would provide the “biggest bang for the buck?” There was considerable overlap in responses:

1. **Private sleeping quarters sufficiently sized to be comfortable** was the most important design feature overall (mentioned by seven of the nine SMEs). Private quarters that provide auditory as well as visual privacy and that do not require continual reconfiguration or set-up were seen as essential for maintaining team health and effective performance on a long-duration mission.
2. **A comfortable space to gather as a whole group**, particularly for meals, was the next most commonly cited design feature (mentioned by five of nine participants).
3. **Habitat flexibility**, in terms of noise, lighting, layout configuration, and stowage was mentioned by two SMEs as being the most critical design characteristic.
4. **Good exercise facilities** was mentioned by one SME as being a critical design feature.

These issues are discussed below, along with the other interview results.

**Private space.** Private space was mentioned by all SMEs as being very important to team health and behavior. As one SME remarked, “You can’t have a good team without privacy.” Private sleeping quarters were seen as essential for long-duration missions. One analog participant described the transition from the initial communal living arrangement to having his own space as a very powerful experience that helped him individually and also benefitted teamwork because the team was, “better able to get on together when they were mentally well.” Other astronauts and analog crew members echoed the importance of a sense of ownership over personal space.
Participants were not asked directly about the optimal or required size of private sleeping quarters but they did generally note that private space should be comfortable, allowing people who cannot externally escape a habitat to at least have a means of internal escape. Several analog participants felt that their private quarters could have been smaller but only because the overall habitat was relatively large and there was ample private workspace. Similarly, one SME noted that the acceptability of current private quarters volume on the ISS is likely partially a function of “found” private space in the rest of the habitat. The SME noted, for example, that crew members on the ISS currently curtain off some areas to create private space for hygiene tasks, even though that was not how those areas were intended to be used, and cautioned that without this found space, current volumes for private quarters and hygiene facilities may not be adequate.

Others noted that as the mission duration increased (in analog environments) there was an increased desire to spend time in private space and that private quarters should be comfortable enough to accommodate this. One SME echoed this sentiment with regards to the ISS, saying that the current size of private quarters is adequate but that larger quarters may be needed for long-duration missions, along with an increased ability to personalize the space.

One factor that may increase the volume requirements for private space is planning for workspace within private crew quarters. Several SMEs noted the importance of being about to work periodically in private quarters (particularly when one did not have another private dedicated workspace). One SME, for example said, only partly joking, that crew members should be issued “sick day” cards so that they had a valid excuse for periodic escape where they could stay in their private quarters to work. A long-duration analog participant noted that crew members on that mission preferred to do independent work in their private quarters and that this tendency increased with the mission duration.

The size of crew quarters notwithstanding, it was important to SMEs that one’s private space be a dedicated area over which one has a sense of ownership, where one can organize (or not) one’s things without worrying how they will affect other crew members, and where one can shut the door. A shared, rotated, or multi-use space that requires continual reconfiguration or setup for sleeping was not viewed as acceptable.

For several astronauts and analog crew members, private space for one’s things was almost as important as private space for oneself. One astronaut, for example, noted the importance of having a predictable place for frequently used personal items (such as books, toothbrush, tools needed first thing in the morning, etc.) in order to stay organized. Another astronaut and several analog crew members describe how their sense of personal space was strongly defined by their things (clothes, personal items, work equipment) and noted that it was important to have their things in their own space and not stored elsewhere.
In addition to private sleeping quarters, other forms of privacy were perceived as important, notably space to be alone but not confined in your quarters (e.g., to record personal videos, play loud music, etc.) and space for private interactions and conversations between two crew members.

**Team social/gathering space.** Beyond individual volume needs, there are team-related volume needs and all SMEs noted the importance of a social space, or team room, where the entire team could gather simultaneously. Whole group activities, particularly cooking and eating but also both passive and active team recreation (for example, one SME noted that some ISS crew members bring ping pong paddles to play with), are seen as critical for building and maintaining team cohesion.

SMEs agreed that the team space needs to be of sufficient volume for all crew members to comfortably fit and many SMEs noted the importance of a table that can comfortably accommodate not only all the crew members, but also all their food, drink, and other items necessary for a particular activity. One NEEMO crew member describes how the crew of six was not able to gather around the table built for four and that this was a significant limitation of the space – a limitation which he felt would have been much more problematic on a longer-duration mission. A Mars-500 crew member similarly describes how although the whole crew was able to fit around the kitchen table, the table was not big enough to comfortably accommodate everyone’s food and drink and that this was a frustration.

In addition to serving as a social space, the team room must facilitate team meetings and other work activities. Again, the central table was seen as important for some of these activities. For example, one winter-over crew member at the Concordia Antarctic Research Station described the importance of having weekly meetings around the table in order to iron out any personal problems, disagreements, and other issues. He further noted that even though it was not designed for the purpose of social space, the industrial workshop was the preferred place for group meetings and socializing (as opposed to the living room) because of the large table where everyone could gather. Another analog crew member similarly described the need for a space where the entire crew can gather and look at one another face-to-face.

In addition to a table around which crew can gather, SMEs also mentioned the need for infrastructure that supports team recreation and team work, such as a large video screen, recording devices. Other team work-related activities (i.e., training) may require some open space and hence, as several SMEs pointed out, flexibility/reconfigurability of the space is important (for example, having a table that can easily be moved or stowed).

In addition to the team room, there may be a need for other social spaces. In particular, one astronaut strongly supported the need to accommodate social exercise, pointing out that
astronauts are used to socializing in the gym on the ground and they want to continue this in space. He also pointed out that in the absence of planned physical games and competitions, crew members tend to invent their own physical competitions, some of which may put them at significant risk for injury. Other SMEs felt that social exercise was not a requirement and noted that many crew members prefer to exercise alone (perhaps while watching videos or listening to music). One SME did point out that while accommodating multiple people in simultaneous exercise may not be necessary from a social standpoint, it may be useful in terms of scheduling. Because so much time is devoted to exercise, reducing this time by accommodating multiple simultaneous exercisers may mean that the exercise space could be freed up for something else at other times in the day.

**Flexibility.** Over half of the SMEs specifically mentioned the importance of a flexible and reconfigurable habitat for supporting team health and behavior. As one astronaut pointed out, the ability for teams to customize the habitat not only helps make it their own, builds cohesion, and makes for a “happy and effective crew” but it also helps ensure that the habitat continues to support the needs of the team over the duration of the mission.

Flexibility is needed at several scales. The ability to make relatively minor changes, such as being able to personalize the space and decorate for special events and being able to control noise, temperature, and lighting is important for day-to-day comfort and support. Other small changes (for example, one analog participant described how a fellow crew member used scavenged wood to make a laptop holder in front of the treadmill so that he could watch videos while exercising) help adapt the space to the specific and sometimes idiosyncratic needs and preferences of the crew. The ability to reconfigure the environment on a larger scale – for example, through partitions, inflatables, or modular structures – becomes more important the longer the mission duration. One analog crew member described the kitchen space as too small for everyone to eat and place their food and drinks on the table. He suggested that if the space could not have been made permanently bigger it may have worked to have a moveable wall so that the kitchen could have extended into the living room for meals and then been shrunk back when the kitchen was not in use to increase the size of the living room.

The need for flexibility in work stations and furnishings was also emphasized. Work spaces need to accommodate private and communal work on a daily basis and different types of work and experiments in different phases of the mission. Multi-use spaces, such as the kitchen and team/living room, need to have flexible furnishings so that, for instance tables and chairs can be stowed or moved when a larger space is required. One analog crew member, for instance, found that the large chairs in the living room were comfortable but difficult to move out of the way when a more open space was required (for example, when making videos). A more flexible (i.e., collapsible) furniture design may have facilitated multi-use of this space. One astronaut
pointed out that the 3D nature of the spaceflight environment offers more opportunities for flexibility than ground-based environments – for example, using both sides of a table to double crew workspace – but that it can be difficult to visualize these opportunities during the on-ground design process.

**Stowage.** Stowage is a critical issue that has implications not only for individual performance and psychological health but for team performance as well – stowage organization (or clutter and disorganization) has the potential to either speed up or slow down performance and task switching. Many of the SMEs interviewed here mentioned the critical roles that efficient stowage and inventory systems play in work efficiency and noted that stowage systems should minimize clutter and allow the crew to find things easily when needed and to re-stow them efficiently. Both astronauts and analog crew members noted problems with stowage inefficiencies and resulting frustration and impediments to efficient task completion. Something as simple as using color coding to help differentiate stowage bags and bays on the ISS was mentioned by one astronaut as a potentially powerful countermeasure with virtually no costs.

Several SMEs noted that stowage and organization are particularly important to consider when moving from interdependent to independent work and vice versa because work transitions make it more difficult to keep track of tools and equipment. Another critical transition point mentioned by several SMEs is crew or team change-overs; again, efficient stowage and inventory (along with procedures to orient new crew members) is critical to work efficiency. As one astronaut noted, many projects have multiple associated tools and pieces of equipment and keeping track of parts and tools can become very complicated when one team must pick up and complete a task that was started by others.

Several SMEs noted that stowage and organization needs are not static and therefore stowage systems should be flexible, with the ability to adapt both according to the desires of the crew and the needs of the moment. One astronaut noted that both temporary storage space and the flexibility to create a system of organization “on the fly” are critical to project and team success.

**Workspace.** SMEs identified several risk factors related to the physical work environment. In some cases, limited real estate (e.g., table space) and resources (e.g., power outlets, snowmobiles, fuel) made it difficult to get independent tasks done. One analog participant noted that private work space was limited and it was sometimes difficult to focus on independent work at the communal work table (although this did have the benefit of keeping people more engaged with other crew members because one could hear conversations and give relevant input at the right moment).
Insufficient space was also cited as a risk factor for collaborative tasks. One analog participant described a task that required careful coordination among several crew members but noted that space limitations meant that the two crew members coordinating the task could not be co-located. This made the task more difficult and introduced risk. In addition to co-location, mutual gaze (the ability for collaborating crew members to make eye contact when necessary) and the ability to view a shared screen/shared data were seen as very important.

Several SMEs noted that because different people (and teams) have different work preferences and because these work preferences and needs can change over time, workplace flexibly is important (for example the ability to move from a communal space to a more private work area or station). A number of SMEs also noted that as part of this flexibility, crew members require mobile technology, such as computer tablets, as well as orientation cues and other infrastructure, such as places to anchor computer tablets or other work/instruction devices. Another analog crew member made the point that flexibility should not increase the overhead of frequent tasks; for himself, work was sometimes a challenge when things needed to be reconfigured before beginning the task or activity. Similarly, an astronaut noted that work spaces sometime occlude one another and that this is a real problem.

Finally, one astronaut expressed the opinion that scheduling is just as, or perhaps more, important to efficient work than the habitat layout.

**Crowding.** Although several astronauts and analog crew member did feel their habitats were crowded – at least at times – crowding was generally not considered problematic in the context of the relatively short-duration missions and/or relatively spacious environments experienced by the SMEs. For example, one astronaut noted that crowding was a problem when their crew was temporarily joined by another crew, leading to problems with scheduling activities such as exercise and congestion in the galley and around the dining table. Because he knew it was temporary, however, he was able to “grin and bear it.” This sentiment was echoed by other crew members and SMEs who experienced short duration or temporary crowded conditions in their habitats (as is the case, for example, when an Antarctic station fills up for the summer or the crew on the ISS is temporarily joined by a Shuttle crew). As one analog crew member noted, “You can tolerate almost anything for fourteen days.”

Crew members did note that if the mission duration were longer under the crowded conditions it would likely have become a problem. As one habitability expert noted, however, they do not have good data to tell us what those problems might be. There are few high-fidelity analogs for long-duration spaceflight; smaller habitats such as the Shuttle and NEEMO tend to be used exclusively for short-duration missions and longer-duration habitats (such as Mir, Skylab, the ISS, and Mars-500) are relatively spacious.
Layout/volume. Several general considerations regarding team-based volume estimates were mentioned by the SMEs. A habitability SME noted that a number of team related volume-driving tasks have been identified, including eat and greet, whole-team recreation, medical tasks, and work activities, but that we need better real-time data to understand volume-driving behaviors. In addition to the volume requirements for specific spaces, there is a need to better understand and model the layout of different functionality zones (e.g., based on compatible/incompatible activities and tasks) in order to determine what layouts would best support the team. Designing efficient translation paths and patterns may also be volume-driving and there is a need to collect data on movement patterns in microgravity. Finally, a better understanding is needed of how much and which spaces can reasonably be multi-use.

One of the astronauts also emphasized the need to consider design and layout in the context of micro/0g, noting that the full use of three dimensions can maximize usable and perceived space and also help avoid a sense of crowding. On one mission, for instance, he described being able to “get away” from people by hanging out on the ceiling. As another SME points out, however, designing 3D habitats will require flexible thinking as well as flexible design; careful consideration will need to be given to how crew members might orient themselves in a particular space and what types of design elements (for example, visual cues, hand holds, and other orientation and navigation aids) will be required.

Design-related nuisance factors. Several SMEs provided examples of habitat-related nuisances that negatively impacted their daily lives and overall performance. One analog crew member, for example, explained how getting to a frequently used module required one to “duck walk” through a small tunnel-like hatch that could only accommodate one person at a time. To make matters worse, accessing the equipment and tools often needed for experiments in that module required navigation through two hatches, making the translation inefficient and frustrating. In part, the frustration stemmed from the design of the translation space and, in part, from the design of the stowage system. Similarly, a crew member with experience in multiple analog environments noted that the overhead for many routine tasks is simply too high in these habitats. Frequent activities, like collecting water and going to the bathroom were big hassles and required significant time. In his opinion, habitat design and procedures should strive to keep overhead time at less than 1 minute for tasks and activities that need to be done more than a couple times per day.

Design elements: noise, lighting, and windows. SMEs noted a number of additional design elements that may impact team health and performance. These included:

Noise. The importance of auditory privacy and sound insulation was mentioned by several SMEs. One analog crew member cited the lack of auditory privacy in the habitat as a big
negative but also noted that it may have played a role in keeping the team from splintering because private/secret conversation among crew member subsets was not possible.

**Lighting.** Lighting was mentioned by several SMEs as being important to both team and individual health. Lighting needs included: sufficient workspace lighting, flexible lighting based on different needs for individual and group tasks and activities, and better insulation from the ambient (or outside) light when needed.

**Windows.** Some SMEs noted that windows would be a useful countermeasure, particularly in the common space. Another SME, however, felt that while windows have significant benefits to individual psychological health, they do not necessarily play a direct role in team health.
Big Issues for Small Spaces: A Summary of Environmental Risks to Team Health and Performance in Long-duration Spaceflight

A synthesis of (1) the relevant literature, (2) insights from crew comments, and (3) results of the operational assessment points to a number of significant environmental risks to team health and performance in spaceflight. These risks are depicted in Figure 1 and are summarized below.

Inadequate Privacy
Astronauts and other experts agree that it is difficult to have a healthy team without adequate privacy, and there is ample evidence to back this up. In addition to the need for individual privacy (most notably in the form of dedicated private quarters), there are additional essential aspects of privacy, including privacy from incompatible activities, dyad/sub-group privacy, privacy of the group from outside observers, and control of the interplay between individual privacy and group member accessibility. Lack of privacy along any of these dimensions can be a significant source of stress and negatively impact not only individual psychological health but also team cohesion and performance.

Inadequate Social Space
Only second to the need for privacy for the SMEs in the operational assessment was the need for a comfortable whole-group social space. This sentiment is echoed in ISS crew comments and supported by the literature. Not only does the team occasionally require a large space to complete training and other collaborative tasks and activities, but many team-focused countermeasures depend on the ability of the entire crew to comfortably be in the same room at the same time. Taken together, these data strongly argue for a “team room” that would comfortably accommodate the entire team across a range of activities.

Crowding
Although crowding does not appear to be a serious problem in current analog and space habitats, this must be viewed in the context of relatively short-duration missions and/or relatively spacious habitats. In other words, the fact that astronauts and analog crew have not experienced significant problems with crowding is likely more a function of the environment than a function of the crew members themselves. We simply do not have good data on the effects of crowding in very small long-duration spaceflight habitats. Based on the existing literature on crowding, however, we must assume that crowding (due to small capsule size, minimal privacy and invasions of personal space) will be a significant risk factor in long-duration spaceflight. The risk of crowding is that it can lead to psychological stress, hostility and intergroup friction, social withdrawal, and reduced supporting behavior – all of which could significantly and negatively impact team health and performance.
Inadequate Habitat Flexibility/Reconfigurability

The flexibility to reconfigure the habitat as required emerged as a critical factor in team health and performance. The needs go well beyond the ability to decorate and personalize the environment (although this is important too) and include the ability to temporarily modify spaces (for example, to create extra or temporary storage or to reconfigure workspace) and the ability to make larger scale or more permanent changes (for example, through moveable partitions or inflatables). Lack of flexibility increases the risk that the habitat will not meet the needs (and changing needs) of the crew.

Incompatible Layout

Vehicle layout is a risk to team performance if it prevents effective and efficient performance of crew tasks or creates unsafe or stressful conditions (Whitmore et al., 2013). Careful thought as to which activities can occur in close proximity and/or can be accommodated in the same multi-use space and which activities are incompatible and best located in separate zones (e.g., clean and dirty activities; quiet and loud activities) is needed to help create a layout that supports team cohesion and performance.

Inadequate Workspace

A supportive workspace must facilitate effective independent work, effective interdependent work and the transition from one task type to another. Add to that the different work preferences of crew members and the substantial volume constraints, and designing a habitat to support team performance becomes a significant challenge.

An environment that supports one type of work may well impede another type of work. For example, independent work that requires mental focus is often best supported by an environment that is at least somewhat enclosed and away from disruptions such as noise and social activity. Lack of these environmental features poses performance risks and can lead to mental fatigue, irritability, cognitive deficits, decreased productivity, and increased errors. However, there are also independent tasks that do not demand one’s full attention (for example, routine maintenance work) and these tasks may in fact benefit from some stimulation such as background music or social engagement; an environment that does not support this type of work poses performance risks due to boredom (e.g., an increased risk of making mistakes). Interdependent work, such as team training or team tasks, typically requires even more social engagement and may best be supported in a more open environment where team members can be co-located, hear each other easily, maintain eye contact, and jointly view relevant data. An environment that does not support this co-presence poses risks to performance, including miscommunication and errors.

Because high performance across different types of work requires a range of work environments, flexibility in workspace design is critical. Crew members should be able to move
to, or create, different work areas depending on task requirements and individual preferences. This flexibility could be facilitated by portable equipment and technology and by collapsible/flexible/repositionable work surfaces and partitions.

**Inadequate Net Habitable Volume**
Even the best design and countermeasures cannot overcome the risks associated with an environment that is fundamentally too small. Determining required volume envelopes for group tasks and activities (e.g., meet and greet, medical tasks, active recreation) requires more research. In addition, methods for determining volume needs that are not task-specific (for example, personal space requirements, translation paths) are also required.

**Inadequate Stowage System**
Both historically and currently, stowage onboard space vehicles has been problematic and has negatively affected stress levels, individual and team performance, and overall perceptions of habitability (Simon and Toups, 2014). This theme was reiterated both in the analysis of crew comments and in the operational assessment results.

**Other Inadequate/Stressful Environmental Features**
Noise and inadequate lighting (or inadequate light control) are frequently mentioned as problematic in space and analog habitats. These factors pose risks not only to physical health and safety, but also to team health and behavior by increasing stress and mental fatigue, causing performance decrements (e.g., from lack of sleep or poor visibility), and (in the case of noise) impeding communication. Other environmental factors, such as uncomfortable temperature and inadequate ventilation can also pose risks.

**Environmental Factors Leading to Decrement in Psychological Health**
When considering team performance, the role of individual psychological health and behavior cannot be ignored. Declines in psychological health and negative individual behavior are themselves risk factors for team health and performance. Therefore, environmental countermeasures that reduce psychological stress (e.g., light, nature, sensory complexity and variability, virtual and real windows, lack of clutter, appropriate noise levels, opportunities for mental restoration) will also help reduce risk to team health and performance.
Inadequate privacy (individual, dyad, group)
Inadequate social space
Crowding
Inadequate flexibility/reconfigurability
Incompatible layout
Inadequate stowage system
Insufficient NHV
Inadequate work space/s
Excessive background noise
Inadequate lighting

Team Health and Performance Decrements due to:
- Intergroup friction
- Loss of team cohesion
- Social withdrawal
- Reduced supporting behavior
- Mental fatigue
- Increased performance errors
- Reduced productivity
- Miscommunication
- Reduced team coordination

Figure 2. Team risk factors in long-duration spaceflight related to incompatible habitat.
Design-Based Countermeasures for Mitigating Risks to Team Health and Performance in Long-duration Spaceflight

As the results from the evidence review and operational assessment show, incompatible habitat design poses a range of risks to team health and performance. Poor design can increase team conflict, decrease supporting behavior, lead to social withdrawal, and impede both individual and collaborative work performance. Good design, on the other hand, can foster positive team interactions, help build team cohesion, and improve work performance, thereby greatly improving the likelihood of a successful mission and a healthy crew.

What is good habitat design from a team health and performance perspective? The highly volume-constrained spacecraft interior must both minimize environmental stressors and maximize support for positive team interactions and performance. Based on our current state of knowledge, the following design-based countermeasures (depicted in Figure 3) should be considered (“recommended” is perhaps too strong a word at this point).

Achieving the Biggest Bang for the Buck

In any discussion of countermeasures, it is important to note that additional spacecraft volume translates to additional mass and that therefore volume-dependent countermeasures for maintaining and promoting team health and performance come at a high cost. Considerable tension exists, then, between what habitability and other experts consider necessary and what engineers and budget-minded people consider possible. Given that the ideal and the possible may never quite meet, we must identify the most critical countermeasures and begin to prioritize.

What is likely to give us the biggest “bang for the buck?” Based on the evidence reviewed here along with SME responses to this very question, the following list of countermeasures provides a starting point for this important discussion:

1. **Private crew quarters.** Private crew quarters are considered essential.
2. **Team/social room.** Whole-team space is considered essential.
3. **Habitat flexibility and reconfigurability.** Flexibility at different scales and time horizons is considered essential.
4. **More efficient and organized stowage system.** Improved stowage organization and inventory is considered essential.
5. **Other low mass countermeasures** are “no brainers” to implement because they are low cost and have a high probability of some risk mitigation. These countermeasures include: noise reduction, appropriate lighting, scheduling, training to set expectations and coping skills, virtual windows, thoughtful layout of activity areas within a specific habitable volume (accommodating, as much as possible, activity separation and efficient translation paths), use of orientation and navigation aids, and use of color.
Figure 3. Countermeasures for reducing habitat-based risk to team health and performance in long-duration spaceflight.

**An Overview of Countermeasures**

**Private space.** Private space and social space will go hand in hand on a long-duration mission. As the architect, Christopher Alexander, writes, "No one can be close to others without also having frequent opportunities to be alone" (Alexander et al., 1977, p. 141). There is widespread agreement that crew members on long-duration missions will require dedicated (i.e., permanent and requiring little or no set-up) private quarters that can comfortably accommodate sleeping, private communication and recreation, and some private work.
Although we do not yet have sufficient data to definitively determine the optimal volume of private sleeping quarters, a long-duration mission may require larger private quarters than those currently on the ISS. An expert panel convened by NASA recently recommended a volume of 5.4 m$^3$ for each individual crew quarter (as compared to current ISS crew quarters of 2.1 m$^3$) because of increased privacy needs on a long-duration mission (Whitmire, et al., 2015). In addition, the panel recommended co-locating individual crew quarters around a semi-private core (large enough for two or more crew members) through which all crew must pass on their way into and out of private quarters in order to help minimize the risk of social withdrawal by promoting regular social contact.

In addition to private crew quarters, spacecraft design must include areas for dyad/small group privacy. Appropriate areas for these semi-private activities might include thresholds between activity zones (particularly if that area incorporates a social artifact such as a window), or an appropriate space in an out-of-the-way activity area (e.g., airlock/suit-up area).

**The team room.** The ability for the entire crew to comfortably gather in the same room is important for collaborative work and activities that build team cohesion. The designated “team room” will necessarily be a multi-function space and should be large enough to comfortably accommodate a range of group activities, including team work/training/meetings, group meal preparation and dining, and passive and active group recreation. Crew members should be able to comfortably orient themselves so that eye contact with one another is possible during group activities.

The design of the space (e.g., décor, furnishings) should clearly demarcate it as a space for the whole team and the design should have built-in flexibility so that it can meet multiple needs. For example, a table in the team room could double as a screen around which the whole group could gather for work/training/entertainment purposes and could be designed to easily stow or collapse when not in use; the space could also be designed to be used in different gravitational orientations for different activities. The inclusion of a large window (or combination window/virtual window) in the team room could increase the sense of volume, provide a social focal point, and enhance mental restoration. More research is needed to determine specific required volume envelopes for team tasks and activities.

**Workspace design.** Although crew tasks may be completed in a variety of spaces (for example, private work may occur in private crew quarters, whole-team tasks may occur in the team room, some experiment-based tasks may occur in the exercise or medical area, and maintenance tasks will be distributed throughout the vehicle), a long-duration mission will likely require dedicated work space (to provide multiple working surfaces and house equipment such as experimental hardware/tools and computers). The volume requirements for this space are highly dependent on the mission, but it is clear that the workspace will need to provide a
balance between the need for individual focus and the need for team interaction. Because
individual productivity is supported by visual and aural privacy and enclosure while
collaborative productivity is supported by visual and aural accessibility, achieving this balance
will require a flexible design.

Flexibility to reorient oneself with respect to others can allow one to transition from visual
privacy to visual accessibility. A simple example of this is the orientation of fixed workstations
at 90° to one another (e.g., as if occupants were at adjacent sides of a table) so that eye contact
can be easily made or avoided (Sommer, 1959 and 1962; Sundstrom, 1984). A more
comprehensive approach might involve easily movable individual workstations or
removable/repositionable workstation panels or other enclosures (particularly enclosures
behind and to one side) in order to moderate visual/social input and send a message regarding
social accessibility.

Aural privacy/accessibility could be moderated through use of individual noise reduction
systems. Variation in lighting (e.g., focused task lighting vs brighter ambient light) could also
help make one more or less aware of the external environment. Finally, the choice of image on
a virtual window may also be modified to either support quiet mental restoration (allowing one
to mentally “be away”) or to increase arousal and orient one toward social interaction. Flexible
design can not only support different work needs but it may also help facilitate switching from
one work/task type to another (e.g., by decreasing or increasing presence of
social/environmental stimulation).

As with all areas of the vehicle or habitat, design must be gravity sensitive, and where zero or
microgravity is assumed, full advantage should be taken of the ability to use all available
volume. Individual workstations, for example, may be accommodated in a smaller volume if
they are placed in different orientations or if both sides of a desk/table are used for work
stations. As with all multi-orientation design, careful thought will need to be given to
appropriate visual orientation cues and interior design elements (for example, the direction of
ambient and task lighting, the placement of hand-holds).

**Designing for flexibility and reconfigurability.** The need for highly flexible social and work
spaces has already been emphasized. Additionally, more general flexibility in interior
configuration and design is important. Over the course of a long-duration mission, volume
constraints (e.g., as stowage transforms from goods to garbage, or as work needs change),
individual and group preferences, and team needs may change. An environment that can
change to accommodate these shifting needs will be important for maintaining team health
and performance. Gravity changes from one phase of a mission to another (e.g., from flight to
orbit to surface operations) will also significantly impact how the habitat can be used and
considerable habitat reconfiguration may be required to use the space safely and efficiently.
A range of flexible design solutions have been suggested, including moveable walls, modular interiors, transformable or stowable furniture, inflatable partitions and modules, temporary stowage solutions, semi-collapsible sleeping quarters, and other flexible designs (see Simon and Toups, 2014, for an overview) but more research is needed on how these solutions would play out in the spaceflight environment. One important factor to consider will be the time and effort required for the various flexibility solutions. Short-term flexibility needs (for example, reconfiguration of work space to vary degree of privacy, reconfiguration of social space to support different activities, and any on-going reconfiguration requirements for private quarters) will need to be designed so that change can be accomplished in a short amount of time with minimal effort. As one analog crew member noted, high time and effort overhead for everyday tasks can lead to frustration and fatigue. A higher time/effort cost would likely be acceptable for making longer-duration modifications.

**Habitat shape.** Research related to team performance and social interaction points to a possible advantage of horizontal/linear spacecraft design (like the ISS) over a vertical (so-called “tin can” or “hockey puck”) design. Horizontal design may more readily lend itself to increased visual and architectural depth (due to the absence of the visually-restrictive intermediate floors in a vertical configuration; Nixon, 1986); this may, in turn, help reduce sense of crowding and allow a balance between visual access and visual enclosure. In addition, a horizontal design may more readily allow an increased number of translations paths, which can increase perceived volume, and help control movement patterns.

**Layout and partitioning of activity zones.** Given the volume constraints, space habitats for long-duration missions must be as multi-use as possible. Yet supporting team health and performance will also require keeping incompatible activities separate. Activities that have been identified as incompatible are dirty/clean (e.g., hygiene/medical) and noisy/quiet (e.g., socializing/sleeping). Partitioning spaces can be done in a variety of ways, including the use of physically separate modules or the partitioning of a larger space through room dividers, doors, walls, furniture and lighting (Simon and Toups, 2014).

In addition to these layout constraints, attention must be paid to circulation paths and translation points. When effectively designed, these “spaces between the spaces” can perform multiple functions, including facilitating movement patterns, increasing architectural depth by partitioning a space into multiple separate areas, providing visual privacy between spaces, and minimizing interruptions to task performance. Paths should be sized to comfortably allow two crew members to pass and could be additionally designed to shift one’s orientation towards the activities in the next space (e.g., reduced lighting as one moves to the private/quiet area, increased lighting and perhaps a change in color as one moves to the team/group area).
Stowage. Stowage systems need to be designed to reduce visual clutter and to make tools and other items easily accessible when and where they are needed. The current rack systems on the ISS are based much more on engineering and industrial ergonomics considerations than on social or functional logic (Cohen, 1990) and there is significant desire across the spaceflight community for a change. However, there is currently not a great deal of imagery for alternatives nor agreement on whether a distributed or central stowage system would be best, although several SMEs did comment that at least a partially distributed stowage system would facilitate co-location of tools and other items with their task areas. Careful design of individual stowage areas (including the use of color, consistent labeling, and design for easy accessibility) would help ensure that frequently used items are most readily accessible and that all items can be found when needed and re-stowed when not. Finally, building flexibility into the stowage system will be important; the team should be able to reconfigure stowage as needs change over the duration of the mission and should have some capacity to create temporary stowage areas as the need arises.

Interior design. Furniture and other design elements are also important parts of the physical environment to consider. As already mentioned, flexible furniture arrangement is important in order to meet a range of needs within a confined volume. Others aspects of interior design should also support the intended functions of a particular area. Particularly relevant with respect to team health is noise reduction, appropriate lighting (which not only improves work efficiency but can also decrease perceptions of crowding), and possibly the use of color to promote an outwards/social orientation or an inward/quiet orientation (for example, by demarcating social space with colors that are more energizing and demarcating private space with colors that are more calming). Lighting is also important to consider from an entrainment perspective. Lighting shifts have been suggested as a method to help temporally sync crew members, and synced temporal orientation is, in turn, associated with enhanced team performance (Mohammed and Nadkarni, 2011).

Interior design elements can also increase perceptions of volume, thereby helping to reduce sense of crowding. Design guidelines for small spaces, as summarized by Simon and Toups (2014), include: providing long sight lines and diagonal views; minimizing clutter (particularly the area above waist height); increasing the ratio of ceiling height to room size; using lighter colors with dark accents; providing more natural light (or facsimile of natural light); and using mirrors, windows or virtual windows.

Windows and external views maybe particularly important. Not only can they improve team health by increasing one’s sense of volume and thereby helping to decrease perceptions of crowding, but they are also an important countermeasure for psychological health. In the
context of a long distance mission, where there may be little to see outside, virtual windows and views can offer similar benefits (see Kearney, 2013 for an overview).

Because most of these guidelines are based on architectural best practices in the Earth-gravity environment, careful thought needs to be given to how they could be best applied to zero and microgravity habitats. In particular, in space habitats different activities and tasks may be completed in different orientations within the same space so that concepts such as “up,” “down,” and “waist-height” are mutable.

**Scheduling, training, and crew selection.** Although not elements of design, scheduling and training will be important countermeasures for helping team members cope with an environment that, no matter how well designed, will never be perfect. Careful scheduling of tasks and other activities with the limitations of the physical habitat in mind can help to distribute crew members throughout the habitat, reduce competition for resources (such as tools and exercise equipment), and provide temporal separation for incompatible work activities. Note, however, that there is strong support for keeping crew members in circadian alignment for a long-duration mission (Simon et al., 2011).

Training will also be important to prepare the crew for the realities of the habitat and to help them use the space wisely (NASA HRP, 2015). Simply being aware of the negative effects of social stressors, for example, may help crew members recognize signs of stress and implement countermeasures to facilitate stress recovery. These countermeasures might include seeking private time and engaging in activities to facilitate recovery from mental fatigue or purposively modifying the environment to better support the task at hand. Setting appropriate expectations is also an important part of dealing with stressors such as crowding, although it is unlikely that this would counterbalance the negative impacts of crowding over a long-duration.

There is undoubtedly some cultural and individual variation in people’s need for environmental attributes, such as amount of personal space, and their ability to cope with environmental stressors such as clutter or lack of privacy. Although there may be some implications of these variances for crew selection, these considerations will likely be dwarfed by the need to select based on other personality and behavioral traits, skillsets, crew availability and political realities.

**Implications for Net Habitable Volume**
A number of the countermeasures with respect to team health and performance highlighted here have volume requirements and hence implications for minimum NHV. These include: the provision of dedicated private, social, and work spaces; activity separation; supportive stowage systems; architectural depth; and possibly the desire to accommodate multiple crew members simultaneously in the exercise area.
There are insufficient data on team task envelopes and other volume requirements to be able to offer definitive NHV recommendations. Recent work done by the NHV consensus panel (Whitmire, 2015), however, offers a starting point. The panel recommended a minimum NHV of 25m³ per person based on a 6 member crew on a long-duration mission. It is very important to note that this volume recommendation came with a number of design caveats regarding overall habitat design attributes, separation of functional areas, and minimum volume and design requirements for each functional area. The recommended overall minimal volume can only be considered “acceptable” in the context of these design and sub-space volume requirements.

Specific minimum NHV estimates aside, it is clear that reducing environmental risk and achieving a supportive team environment with *minimum* volume will require *maximum* consideration of habitat design.
**Research and Operational Recommendations**

Habitability issues related to team health and performance over long-duration missions in spaceflight habitats (or other ICE environments, for that matter) are vastly understudied and more research is needed both in terms of understanding environmental risks in long-duration spaceflight and in terms of designing effective countermeasures for mitigating that risk.

Analysis and synthesis of the data from the evidence review, crew comments, and operational assessment highlight where we might get the most bang for our research buck. Specifically, research should prioritize the largest risk factors where significant gaps in our knowledge exist. Research projects should both extend our understanding of the nature of the risk and inform the development and testing of countermeasures to help mitigate risk.

Habitat-based risk factors for team health and performance are presented in Table 2, along with research recommendations related to those risks and a rating of research priority. Note that a low research priority does not mean that a risk is less significant or that developing countermeasures related to that risk are lower priority; rather, it means that that particular risk area and associated countermeasures are already reasonably well-understood and that our current knowledge is more developed to inform design.

High priority research areas are discussed more fully below, along with several operational recommendations, based on well-understood risks and countermeasures.

**Table 2. Research Priorities and Recommendations Related to Team Health and Performance in the Context of Long-duration Spaceflight Habitats.**

<table>
<thead>
<tr>
<th>Habitat-Based Risk Factors for Team Health and Performance</th>
<th>Habitat-Based Countermeasures</th>
<th>Research Recommendations</th>
<th>Research Priority</th>
</tr>
</thead>
<tbody>
<tr>
<td>Lack of/inadequate privacy</td>
<td>• Private crew quarters</td>
<td>Research needed on:</td>
<td>High</td>
</tr>
<tr>
<td></td>
<td></td>
<td>• minimum required volume</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>• design elements (e.g., windows, semi-collapsible and other volume saving systems) that might allow volume reductions</td>
<td></td>
</tr>
<tr>
<td>Inadequate stowage system</td>
<td>• Implement effective and flexible system of tool/item inventory and task scheduling</td>
<td>• develop and test effective, efficient, stowage systems, including:</td>
<td>High</td>
</tr>
<tr>
<td></td>
<td>• Provide at least some point-of-use stowage</td>
<td>– physical stowage systems</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>– inventory tracking systems</td>
<td></td>
</tr>
<tr>
<td>Inability to reconfigure environment as required</td>
<td>• Design for flexibility</td>
<td>• develop and test approaches and technologies for the reconfigurability of spacecraft interiors and also for flexible workspaces, including research on:</td>
<td>High</td>
</tr>
</tbody>
</table>

45
| Insufficient NHV for team tasks and activities | • Design for sufficient NHV not only overall but within each functional area | • Develop and implement methods for determining group task/activity volume envelopes across range of activities and scenarios (e.g., eat and greet, medical procedures, training, recreation, translation)  
• Develop models of NHV based on these determinations and on other volume requirements (e.g., incompatible activity separation) | High |
| Feeling crowded/personal space violations | • Increase perceived volume through design (e.g., spatial depth, distant sight lines, lack of clutter, etc.)  
• Dedicated translation paths sized for two crew members  
• Appropriate scheduling of tasks and crew member locations | Strong support for design recommendations exists (based on large body of short and long-duration research, albeit mostly in non-space/analog environment). Additional research would be useful on:  
• task scheduling for minimization of crowding  
• personal space requirements for various activities and in various scenarios (including translation)  
• effect of social crowding on performance in high fidelity analogs with astronaut-like population  
• effects of design elements (e.g., layout, configuration, architectural depth, lighting, windows, enclosure) on crowding perception and performance in high fidelity environments and over long-durations | Medium |
| Inadequate workspace/s | • Size and design space to facilitate independent work, interdependent work, and task-switching  
• Incorporate flexible design elements (e.g., repositionable desks, reconfigurable partitions, and flexible lighting) | • What aspects of the environment support individual focused work? What aspects support collaborative work? How can flexibility be designed into the workspace/s so that both individual and group work can be supported?  
• If task switching is found to be a significant risk factor (and this has yet to be determined), what impact does environmental design have on task switching? Can the physical environment be harnessed to facilitate task switching? | Medium |
| Incompatible layout | • Separate incompatible activities | There is strong existing support for separating incompatible activities. Research needs are low, although additional work is required to model and evaluate various layouts options | Low |
and determine how this affects NHV requirements. New designs/habitats should be specifically assessed for compatibility of layout.

| Lack of/inadequate social space | Team room with design elements that maximize perception of volume and comfortably support a range of whole-crew activities | Low research needs (beyond those required for determining team-based volume envelopes). There is strong existing support for design criteria. New designs/habitats should be specifically assessed for quality and acceptability of team room. | Low |
| Lack of/inadequate semi-private space | Provision of area/s for semi-private activities, such as conversations or quiet social activities not involving the whole group | Additional research not required – provisions of semi-private space should be addressed early in design process. New designs/habitats should be specifically assessed for adequacy of semi-private space. | Low |
| Inadequate lighting | Provide adequate and flexible general and task lighting Provide light-based support for circadian entrainment | Low research needs as issues are understood and suitable technology exists – more a matter of incorporating good design/technology early in the process. New designs/habitats should be specifically assessed for adequacy of lighting. | Low |
| Excessive background noise | Design for noise reduction/muffling Provide systems for localized noise reduction/cancellation | Low research needs as good practices and technology exist – more a matter of incorporating good design/technology early in the process. New designs/habitats should be specifically assessed for adequacy of noise reduction. | Low |

**Discussion of High Research Priority Areas**

**Private crew quarters.** Strong evidence exists that having private crew quarters will be a critical countermeasure for maintaining team health and performance in long-duration space missions. There is much less evidence, however, for exactly how large these quarters need to be and how they should best be designed. SMEs have come up with a “best guess” volume of 5.4 m³, based on available data (Whitmire et al., 2015) but the large cost of the additional mass associated with this volume will continue to exert downward pressure on this estimate. Any methods for reducing the overall volume of private quarters would be most welcome by flight engineers, but such a reduction cannot occur at the expense of individual and team health and performance.

Targeted research should compare the benefits and costs of various sized crew quarters in a high fidelity long-duration analog. The ISS may not be ideal for the targeted study of private space volume and design requirements because the overall size of the habitat (and thus the ratio of private space to overall volume) is much larger than would be expected in a long-duration vehicle. Many ground-based analogs will have the same problem (for example,
Antarctic stations, Mars-500) because not only is the overall habitat large, but the private quarters themselves are quite large.

In tandem with (or preceding) studies of volume, research on private quarters should explore designs for flexible or semi-collapsible private quarter solutions to determine whether this would be acceptable and feasible in a long-duration mission. Such systems should retain individual quarters, allow for quick and easy reconfiguration, and allow private items within the space to remain in place during any reconfiguration. Other aspects of private crew quarter design that may help to compensate for a reduction in volume – for example, the inclusion of windows, virtual windows, or virtual reality systems (like those currently implemented in HERA) – should also be explored.

**Flexible/reconfigurable design.** Design-based research is needed to develop and test approaches and technologies for the reconfigurability of spacecraft interiors and also for flexible workspaces that support both independent and interdependent work and that facilitate the transitions between the two. Research should be conducted with emphases on both individual environmental elements (for example, reconfigurable team tables or workspace furniture) and also on the use of flexible structural elements, such as removable/stowable wall systems, modular layout systems, and inflatable designs. This research would not necessarily require a long-duration analog, although the functionality of candidate designs would eventually need to be tested in a microgravity environment.

In addition to design-based research, on-going research should be conducted to explore how the crew’s spatial needs and preferences change over time so that flexible designs will accommodate the anticipated range of desired spatial transformations.

**Efficient human-appropriate stowage.** Inadequate stowage is a significant risk factor for both individual and team health and performance and design-based research is clearly needed on developing and testing effective, efficient, and possibly distributed, stowage systems (including both hardware and software, scheduling and inventory tracking, aspects of stowage) that meet human needs while minimizing volume requirements. Much of this research could be performed in mock-ups and shorter-duration ground-based analogs.

**Team-based net habitable volume requirements.** An important starting point for determining minimum required NHV is the calculation of individual and multi-person task/activity envelopes across a range of scenarios (Whitmore et al., 2013). Although there has been considerable work done on estimating volume envelopes for individuals completing different tasks and in different orientations, more research is needed related to volume requirements for team tasks and activities (Thaxton et al., 2012).
In particular, we need a better understanding of team behavior (including personal space preferences) and volume requirements during team-based meet and greet activities, medical tasks, active recreation and exercise, and other group tasks and activities. Research should explore a range of scenarios for these activities (e.g., different medical scenarios, different group size scenarios, different translation scenarios) across a range of orientations. Initial research could be conducted in a laboratory setting. Subsequent (or concurrent) research should be conducted on the ISS to observe real-time/place behaviors and volume requirements.

**Operational Recommendations**

Synthesis of the data from the evidence review and operational assessment yielded several countermeasures for which there is strong existing support and that can be appropriately generalized to the long-duration spaceflight context. Some of these countermeasures (see Table 2) are most relevant in the context of future habitat design, but several are applicable to current operations.

Operational recommendations include:

**Schedule tasks for minimization of crowding and maximization of incompatible activity separation.** Scheduling of work tasks and other activities should be done with an eye toward distributing crew members throughout the habitat, reducing competition for resources such as tools and exercise equipment, and providing separation (temporal, spatial, visual, noise) for incompatible work activities. Note also that scheduling can be used to support team cohesion, for example by facilitating shared group meals.

**Maximize efficiency of current stowage systems and schedule stowage-related activities appropriately.** Based on the evidence here, inadequate stowage is a significant risk factor for team health and performance and improved stowage systems are clearly desired. In terms of current operations, however, current stowage systems can be improved to help reduce associated risks. Simple things, like increased use of labeling and color coding could improve stowage efficiency. In addition, task time estimates and scheduling need to include adequate time for unstowing/stowing task-related tools and equipment, keeping in mind that these activities may take considerably more time in reality than in modeling. Particular attention should be made to stowage efficiency and scheduling during crew/team change overs.

**Bolster training related to team health and habitability.** Training is an important first line of defense for helping lower team risk factors. Although psychological factors training is currently included in the astronaut training program, sessions are abbreviated, tend to focus on individual psychological health concerns and countermeasures, and do not necessarily sufficiently cover team health and habitat related countermeasures. Additional training
focused on team health, including risk factors, problem awareness, and habitat-based (and other) countermeasures would be a useful addition to current training programs and should certainly be a part of training programs geared at long-duration missions.

**Collect additional data on team and habit factors in current operations.** Because there is a significant lack of data on team health and habitability, opportunities for data collection in current operations should be explored. These data would help inform both current operations and future research. One opportunity for data collection is the modification of existing data collection tools (discussed in more detail below).

**Modifying Existing Data Collection Tools**
Several data collection tools already exist – notably astronaut debrief interviews and the iSHORT questionnaire – and with some additions could be used to collect data related to the habitat and team health. A cautious approach must be taken to extrapolating these data to long-duration space exploration, however, because the ISS is not a particularly high fidelity analog and data may therefore not be directly applicable to smaller habitats and longer-duration missions. And as with all questionnaire and survey/interview items, pre-testing (and subsequent modification) of the proposed questions would be essential.

**Debrief Interview.** Current debrief questions for ISS crew members are largely focused on individual responses to the habitat. It would be useful to extend these questions to capture insights and opinions regarding the habitat and team functioning/performance. The phrase, “living and working together as a team” is proposed to focus attention on the team while encompassing issues related both to team cohesion and team performance (two important components of team health). Potential questions include:

- Do you feel that the overall design of the habitat (layout, design elements, and NHV) supported living and working together as a team? Do you have any suggestions for the design of future vehicles that would make it easier for the team to work together? To live together?

- Add “Did you feel that you had adequate volume for group tasks and activities?” to the current U6-3 question (“Did you feel that you had adequate volume to perform your tasks? Did you feel that you had adequate volume from a psychological standpoint?”).

In light of the importance that habitat flexibility will likely have in design for long-duration spaceflight, it would also be useful to begin gathering more targeted data on whether and how environmental needs change over time and how these changing preferences and needs can be accommodated. Towards this end, potential questions on flexibility include:
- Were there any changes to the habitat (either temporary or more permanent) that you or your teammates made over the course of the mission to improve living and working together as a team? [*or this could be phrased simply as, “... to improve living and working conditions?”]*

- What changes or modifications, if any, (big or small, temporary or permanent) would you have liked to make to the habitat over the course of the mission to better support living and working together as a team? [*or simply, “... to improve living or working conditions?”]*

- Add “habitat flexibility/reconfigurability” to the list of items in the current U6-7 question ("Do you have any additional suggestions you would like to make for future exploration programs regarding human centered design, habitability, level of autonomy, planning considerations, crew comfort (specific smells, wall color, home/Earth amenities)?").

**The iSHORT questionnaire.** The iSHORTquestionnaire is another instrument used for crew debriefs. Current questions (as of this report) 15-17 ask about specific aspects of the habitat and capture an overall rating, recorded on a 5-point Likert scale from completely unacceptable to completely acceptable. In this section, it may be useful to include additional questions on “Social/Team Space” and on “Habitat Flexibility/Adaptability.”
References


Appendix A: Operational Assessment Interview Protocol

Introduction

*Introduce self and project with additional remarks tailored to individual SME, where appropriate.*

Questions

*(Individual SMEs were asked a subset of the following questions, with the ordering depending on the flow of the interview and prompts in parentheses used only as needed. The final question was asked of all SMEs.)*

1. Are there any aspects of the physical environment (for example you might think in terms of layout, overall volume, specific spaces, or other design elements) that make it a challenge for a team to work together or to get along? [Specific examples?]
2. In terms of habitat design, what do you think are the most important aspects of design, the important things to think about, for supporting performance – facilitating team cohesion and collaborative work?
3. Because most space and analog habitats are relatively small confined space, feeling crowded is sometimes an issue...
   a. Was crowding a problem for you or your team on your missions? Can you imagine that it might have become a problem in a longer-duration mission? How did crowding affect the team (e.g., interactions, performance, cohesion)? [Specific examples?]
   b. In what areas or during which activities was crowding most noticeable or most problematic?
   c. Are there any ways – besides simply increasing the volume of the habitat – that you think might help reduce feelings of crowding (e.g., layout or configuration, linear vs open, visual access and exposure, external views, private space, etc.)
   d. Related to crowding is perception of privacy. How important do you think privacy is for team health?
4. How important do you think it is to have a space where the entire team can gather?
   a. What types of activities should this space support?
   b. Are there other important design considerations for a group space?
5. Based on your varied experiences, how do you think the overall layout of the spaceflight environment (the number and configuration of spaces) affects team relationships or team performance? [Specific examples?]
   a. Based on your experiences, do you think that from a team perspective some layouts are better than others? How so?
6. I’m curious as to how team environmental preferences and needs might have changed over time? In terms of how and where teams like to work? Team preferences for how to configure the space? Need for privacy?
7. Part of effective team performance is the ability for individuals to efficiently get independent work done. There are many tasks that must be completed independently but there are also many interdependent tasks that require collaboration among team members.
   a. In your experiences are there aspects of the environment that have made it challenging to get work done? [Specific examples?]
   b. What type of physical environment (specific layout, area/s or design) best supports independent work? What environmental changes would you make to better support individual work?

8. The flip side of independent work is interdependent work where one or more crew members need to work collaboratively to complete a task.
   a. In your experiences are there aspects of the environment that have made it a challenge for teams to complete collaborative tasks efficiently and effectively? [Specific examples?]
   b. What type of physical environment (specific layout, area/s or design) best supports collaborative work? What environmental changes would you make to better support team tasks?

9. There is some concern that switching from one task type to another, for example, from independent work to collaborative tasks may become more difficult for crew members, particularly over a long-duration mission.
   a. Are you aware of any problems with task switching?
   b. Do you think the environment might help support switching from one task type to another?
   c. How might the environment be changed or modified to help prepare crew members to switch to a different task type (e.g., layout, flexible privacy levels, lighting, noise, inward vs outward orientation)?

10. If you were talking to space designers or architects trying to figure out how best to design a capsule or habitat specifically to support and enhance team performance, what do you think is the most important thing for them to know? What do you think would give the biggest bang for the buck in terms of team performance?

Thank you so much for talking with me today and sharing your thoughts.
### Title:
Team Health and Performance in Spaceflight Habitats
Risks, Countermeasures, and Research Recommendations

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### Abstract:
Incompatible spaceflight habitat design is a significant risk to team health and performance in long-duration missions, yet we lack sufficient data regarding the nature of that risk and how best to mitigate it. This study begins to address those knowledge gaps through a review of relevant evidence regarding risks and countermeasures and an operational assessment providing additional insights from subject matter experts, including space and analog crew members. Based on these data sources, promising countermeasures are identified and recommendations and priorities for future research are provided.

### Subject Terms:
team health and performance, space vehicle habitability, countermeasures, net habitable volume (NHV), risk factors

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