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Mitigating Risks to Psychological and Behavioral Health in Long-Duration Spaceflight:

Towards a Portfolio of Countermeasures

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Executive Summary

This study, based on extensive literature reviews and expert interviews, provides an in-depth look at the environmental stressors associated with long-duration spaceflight environments, outlines the risks that those stressors pose for psychological and behavioral health, and recommends a portfolio of countermeasures to help mitigate those risks.

If one were to design a place as a mismatch between what humans need for psychological health and effective functioning and what the environment provides, it might look much like the interior of a modern space vehicle. Even as the physical hardships of spaceflight are addressed, the very nature of traditional spaceflight environments – characterized by extreme sensory reduction, social isolation and monotony, limited space and privacy, periods of both too much and too little work, lack of control and autonomy, distraction from noise and visual clutter, and few opportunities for mental restoration and stress reduction – can erode psychological health and negatively impact behavior and functioning.

What are the consequences of living and working in such an extreme environment? A wide range of effects related to psychological health and well-being have been reported in spaceflight and analog environments, including:

- ***Performance and behavioral decrements*** (reduced productivity, increased error rate, faulty decision making, reduced ability to inhibit impulses, increased risky or violent behavior)
- ***Cognitive deficits and neurological changes*** (reduced ability to pay attention, lapses in memory, problems with spatial orientation, changes in sensory perception)
- ***Negative impacts on emotion and mood*** (increased irritability, depression, inconsistent motivation)
- ***Interpersonal conflict***
- ***Sleep problems and fatigue***

How can risks to psychological health in spaceflight, particularly in long-duration spaceflight, be mitigated? The extreme nature of these environments means that there is no single countermeasure that can sufficiently mitigate risk. Rather, what is required is a comprehensive risk mitigation strategy – or *portfolio of countermeasures* – that addresses the range of environmental stressors and offers crew members individual choice. An effective countermeasure portfolio would seek to reduce risk through three avenues:

1) Improve human-environment compatibility by reducing environmental stressors through the modification of the physical, work and social environments.

2) Improve human-environment compatibility by increasing the capacity of the crew to cope with the spaceflight environment through careful crew selection and training.
3) Provide crew with effective mechanisms and strategies for coping with and recovering from environmental stressors that cannot be eliminated.

More specifically, countermeasures should:

- ***Reduce distractions and stressors*** related to capsule design and mission planning. Examples include mechanisms for reduction of noise and visual clutter, designing to improve orientation, providing sufficient lighting, and planning and scheduling appropriate workloads.
- ***Improve crew response to stressors in the spaceflight environment*** through crew selection (based on both individual and group traits), training on issues such as conflict resolution and stress reduction techniques, and high-fidelity experience of extended duration.
- ***Stimulate the brain*** both through meaningful external sensory stimuli (e.g., visual, auditory, gustatory, and olfactory) and through intellectual stimuli, thereby helping to ameliorate some of the neural and psychological impacts of low sensory and monotonous environments and of boredom.
- ***Promote the recovery of directed attention and the reduction of overall stress,*** through, for example, opportunities for privacy, simulated nature experiences, virtual windows, and meditation, thereby helping to maintain cognitive functioning and appropriate behavior and improving resiliency.
- ***Provide social support and social interaction,*** for example, by facilitating communication with family and friends and providing access to on-ground and virtual psychological support services.
- ***Foster group cohesion and positive group dynamics,*** through mechanisms such as pre-mission training, in-flight games and activities, and opportunities for the privacy needed to recover from social stressors.

Study Overview

This study consisted of extensive literature reviews and interviews with a range of subject matter experts. Study results provide a framework for understanding the risks to psychological and behavioral health in spaceflight and highlight specific recommendations for an integrated countermeasure portfolio to mitigate those risks. The report is organized in four sections.

Section One provides a framework for understanding the environmental risk factors related to behavioral health and performance during long-duration spaceflight and details the observed consequences of those risks. This section is based on an extensive literature review across a broad range of fields, including: spaceflight and analog studies (e.g., Antarctic research stations, prisons); environmental, evolutionary, and social psychology; and cognitive science.

Section Two provides a review of the empirical evidence regarding specific countermeasures to reduce the risks associated with isolated, confined, and extreme environments. This section identifies which countermeasures may be particularly effective in reducing environmental stressors and maintaining psychological health and well-being in spaceflight environments.

Section Three moves beyond the current literature by providing an operational assessment based on interviews with ten subject matter experts in fields relevant to psychological health in long-duration spaceflight. Results from this assessment offer additional insights regarding countermeasures.

Finally, *Section Four* integrates lessons learned from the literature review, evidence review, and operational assessment to form specific recommendations for the development of a countermeasure portfolio. In addition, research needs regarding countermeasures are discussed.

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1. A Framework for Understanding the Environmental Risk Factors Related to Behavioral Health and Performance during Long-Duration Spaceflight

INTRODUCTION

No matter how well engineered the spacecraft nor how well designed the mission, the success of manned space missions ultimately depends on the performance of the crew. In the early years of space exploration, the major concerns regarding the crew were necessarily survival and physical functioning and a great deal of important work was done on the effects of the space environment on physical health and on the identification of countermeasures (such as exercise) to help mitigate some of the negative physical effects of spaceflight (Lebedinskiy et al., 1964; Suedfeld and Steel 2000). As technology for surviving and living in space advanced, attention turned to the importance of psychological factors in mission success (Clearwater, 1988). The psychological functioning and well-being of the crew became increasingly important concerns as mission duration increased. By the mid-1980s, Oleg Gazenko, then head of Soviet space medicine, concluded that the limitations of living in space are not physical, but psychological (Oberg and Oberg, 1986).

A successful crew must remain clear-headed and productive and maintain good judgment and interpersonal relationships. Maximizing and maintaining mental functioning and psychological well-being in the context of an extended stay in a confined space, with sensory monotony, social isolation, constant threat of danger, and extreme physical demands – in short, an environment that is arguably not conducive to effective human functioning – is, however, a challenge. A host of negative psychological effects have been reported in space and space analog environments, including reduced productivity, faulty decision making, lapses in memory and attention, inconsistent motivation, depression, sleep disturbances, fatigue, and interpersonal conflict (Committee on Space Biology and Medicine, 1998; Vakoch, 2011; Mcphee and Charles, 2009; Harrison et al., 1991). As mission duration increases, we would expect an increase in these problems (Natani and Shurley, 1974; Suedfeld, 1980; Weybrew and Noddin, 1979).

How can psychological risk factors in long-duration spaceflight be mitigated? This question has been highlighted by NASA as one requiring further study (NASA Human Research Roadmap, 2012; Committee on Space Biology and Medicine, 1998). Of particular interest is the impact of the spaceflight environment on psychological health and on the identification of countermeasures to help mitigate environmental risks. The goal is not only to maintain well-being among the crew during and after the mission, but to support effective crew functioning, reduce psychological and behavioral risk factors, and help ensure mission success.

Psychological Risk Factors in Long-Duration Spaceflight: Insights from Environmental Psychology

When exploring the effects of the spaceflight environment on human behavior and psychological well-being, Suedfeld (1991) cautions that the focus must not be solely on the environment, but on the *interaction* between people and the environment. He argues that because the environment is filtered through human psychological and physiological information-processing systems, an individual's *experience* of the environment is a function of both the environment and the person. The field of environmental psychology shares this perspective and hence provides an ideal lens through which to view the psychology of spaceflight.

Environmental psychology is concerned with the interrelationships between people and their environments (Stokols and Altman, 1987; Garling and Golledge 1993) and explores the impact of environments on human cognition, behavior, and well-being. Some environments support effective cognitive functioning, foster positive social dynamics, and encourage reasonable behavior. Other environments have been shown to contribute to a host of behavioral and psychological problems, including impaired attentional capacity, difficulty with planning and problem solving, inability to control anger or cope with minor irritations, helplessness, and other impaired or diminished functioning (Bechtel and Churchman, 2002; Berman et al., 2008; Garling and Golledge, 1993; Kaplan and Kaplan, 1982; Sundstrom, et al., 1996). Spaceflight and other isolated, confined and extreme (ICE) environments are examples of environments that we would expect to be associated with a range of problems. Humans evolved over millions of years in environments quite unlike spaceflight and other ICE environments, and they are in many ways ill-suited for functioning in these extreme environments – not merely because of the environmental characteristics per say (e.g., extreme temperatures, radiation), but because of the way these environments fail to support the way in which humans have evolved to function best.

A central theme in environmental psychology is the notion of the fit of the environment with human abilities, needs, purposes, and inclinations. The goal is not only to predict behavior in specific environments and situations, but to understand and create environments that are most suitable for people – that is, that support effective functioning and reasonable behavior (Stokols, 1977; Wicker, 1979; Kaplan and Talbot, 1983; Edwards and Cooper, 1990; Jansen and Kristof-Brown, 2006; Kaplan and Kaplan, 2009). A mismatch between an individual and the environment – for example, between the demands of ICE environments and human needs and information processing capabilities – generates stress, and can cause a range of negative psychological, physiological, and behavioral outcomes. A good fit between an individual and their environment, on the other hand, supports effective functioning and reasonable behavior (Edwards, 1991; Kristof, 1996; Vischer 2007; Kaplan and Kaplan 2009).

The overwhelming evidence of the importance of environmental compatibility to human well-being begs the questions of what are the characteristics of human-compatible environments and, further, what insights does the concept of human environment compatibility provide with respect to long-duration spaceflight environments? To answer these questions, we must first consider some fundamental characteristics of human nature. Understanding human nature and needs enables one to characterize the environments that will best support these needs, predict what will happen when these needs are not met, and design effective countermeasures to help mitigate the negative effects of environments with poor compatibility.

HUMAN ENVIRONMENT COMPATIBILITY: AN OVERVIEW

The Nature of People

While person-environment compatibility does depend to some extent on individual idiosyncrasies (e.g., specific skills, abilities, goals), much can be said about the environmental requirements that people, in general, have. Many of these requirements stem from the fact that humans are information-based social animals. These characteristics are best understood in the context of the environment in which we evolved.

Humans as infovores

When our early ancestors left the trees for the savannah, they would have found themselves in a complex and uncertain environment where many of the evolutionary niches were already taken. These early humans were neither particularly strong nor fast, they were neither large and threatening nor small and unobtrusive. They did have one big advantage, however: they were adroit at processing and using information. Probably because of their binocular vision, and the ability to manipulate objects that their opposable thumbs gave them, early humans had developed the capacity to separate objects from ground, to mentally represent objects in the environment, and to recall these representations even when the object was no longer there. Although we tend to take these abilities for granted, they are not widely shared in the animal kingdom and would have had a huge survival benefit for our early ancestors (Campbell, 1974; Kaplan and Kaplan, 1978; Lachman and Lachman, 1979; Sterelny, 2003).

Over the past 15 million years of evolution, humans have capitalized on their early cognitive abilities and have evolved sophisticated information processing systems. Humans are able to receive and integrate important sensory information from multiple sources, analyze and store this information, and use their knowledge to find their way around, predict, plan, and make decisions (Kaplan and Kaplan, 1982; Sterelny, 2003). So great is our relationship with information that humans have been called "infovores" (Biederman and Vessel, 2006). Sensory information, particularly that from the natural environment in which humans evolved, is so important to human functioning, in fact, that a lack of sensory stimulation leads to stunted brain development and a host of psychological and behavioral problems (Daffner, 2010; Hebb, 1980).

At the same time that humans evolved their complex information processing skills, they also evolved an interest in and concern about acquiring and using information. From an evolutionary perspective, we could not afford to be neutral about information – our survival, after all, depended on it. As a result, cognition and emotion are inextricably linked (Kaplan and Kaplan, 2009; Gray et al, 2002; Leventhal and Scherer, 1987). Humans care deeply about knowledge and information – we derive great pleasure from acquiring and competently using knowledge and great pain from being confused, lost, or bored (Kaplan and Kaplan, 1982).

Understanding and exploration: Our ambivalent nature. Because people are so reliant on their knowledge, they tend to prefer what they know and to feel most comfortable when they are able to understand and make sense of their environment. On the other hand, because our survival depended on constantly updating and acquiring new knowledge, people tend to get bored by the same old thing and constantly seek out challenges and ways to expand their horizons. Those self-selecting to explore space and other extreme environments are particularly high on the need

for challenge (Santy, 1994). These simultaneous and often conflicting needs for understanding and exploration are what D.O. Hebb (1972) calls our "ambivalent nature". When the need for understanding is not met, we can feel confused, overwhelmed and helpless. When the need for exploration is not met, we can feel bored and disengaged. In either case, the short term consequence is mental pain. If these needs are not met in the long term, the consequences are more grave and can seriously impair one's ability to function (Kaplan and Kaplan, 1982).

The need for stimulation. People are arguably at their best and happiest when they skim the border between understanding and exploration; when they are challenged without being overwhelmed. This is often described as a "flow" state (Csikszentmihalyi, 1990). Evidence for people's need for mental stimulation has led some researchers to posit an optimal level of stimulation (e.g., Zuckerman, 1971) – the theory being that getting the correct level of sensory stimulation is crucial to happiness and optimum performance (Hebb, 1955; Berlyne, 1970). However, our simultaneous need for understanding means that it is not simply the level of stimulation or arousal that is important, but also the pattern, or meaning, of that stimulation (Gallagher, 1993).

Direct evidence for the importance of stimuli richness and pattern to emotional well-being comes from Biederman and Vessel's (2006) study of cognitive reactions to a range of visual scenes. Study participants were presented with scenes that varied both in terms of complexity and interpretability and their cortical activity and preference ratings related to each scene were recorded. Highly preferred scenes were those that were rich in information (complex) and also richly interpretable (a coherent pattern with a high number of mental associations). Particularly high in preference were scenes of nature. Based on measures of cortical activity as participants viewed the different scenes, Biederman and Vessel posit that preference is mediated by the stimulation of opioid receptors in the brain (the release of opioids leads to a feeling of pleasure) as the areas of the brain associated with recognition and association have a high density of mu-opioid receptors (Lewis et al., 1981). Although the focus of their study was on the visual system and perceptual pleasure, there is evidence that other sensory systems function similarly in terms of their response to complexity and coherence (e.g., Goldstein, 1980).

The relationship between cognition – specifically the strength and pattern of cognitive activity – and affect is captured in Kaplan's (1991) theory of cognitive clarity. He uses the terms cognitive clarity to describe a pleasurable state of mind characterized by cognitive activity that has both high focus and extent. Focus refers to an intensity of cognitive activity within a strongly interconnected knowledge structure. Extent refers to the degree to which the associated activity fills one's mental space. A state of cognitive clarity is hypothesized to evoke pleasure while a lack of clarity is hypothesized to evoke mental pain.

Lack of clarity can result from diffuse cognitive activity with insufficient focus (for example a scene or situation that provides little meaningful stimulation) or cognitive activity that is disorganized (for example a scene or situation that may be high in stimulation but that lacks interpretability). It can also result from activity that may be focused but that lacks extent – for example, a highly familiar scene or situation that is so well learned that its associated mental structure has become quite compact. (This later cause of lack of clarity is consistent with Biederman and Vessel's data showing that preference for scenes tended to decline with repetition

and that this was associated with a reduction in overall cortical activity in the opioid-rich areas of the brain.)

The various manifestations of clarity failure have different emotional consequences (e.g., boredom or confusion) but the end result is mental pain. Just as physical pain and pleasure are adaptive in that they cause one to approach or avoid things in the environment, so is mental pain adaptive. The pain associated with confusion, or lack of understanding, would lead one to avoid situations or environments about which one lacks sufficient knowledge to function effectively. On the other hand, the pain associated with boredom encourages one to stop spending time with what is already familiar and instead to explore new environments and possibly acquire new information that may be useful in the future (Smith and Ellsworth, 1985; Hebb, 1949; Kaplan and Kaplan, 1982).

Cognitive clarity can be supported by an external environment that draws attention and provides a rich, coherent, and meaningful set of stimuli – the natural environments in which humans evolved are particularly effective in inducing a state of cognitive clarity. Clarity can also be achieved via the internal environment of the mind – namely one's thoughts, ideas, and plans. In both cases, what is important is not simply the amount of stimulation but the meaning and organization of that stimulation.

The theory of cognitive clarity and supporting evidence suggest that there is not an optimal level of stimulation for humans per say, but rather that optimal environments are those with both high levels of stimulation and a high degree of stimuli meaning and organization.

Managing stimuli in a complex world: Attention and attention fatigue. Although humans rely on and care deeply about information, they cannot possibly capture and process the vast amount of information present in the environment at any given time. Environmental stimuli are virtually unlimited, while the amount of information the human brain can actively work with at one time is severely limited (Miller, 1956; Mandler 1975; Weisberg, 1980). How can we select the most important information and strive to maintain cognitive clarity in the face of the plethora of stimuli the environment has on offer? That is the role of attention. Or more precisely, of several different attentional mechanisms (James, 1892; Posner and Boies, 1971).

Two of the most important types of attention are *directed attention* (also called voluntary, goal-directed, and top down) and *involuntary attention* (also called indirect, stimulus-driven, or bottom-up) (James, 1892; Kaplan, 1995; Asplund et al., 2010; Posner, 1995). These two forms of attention are supported largely by different neural systems, but both are inhibitory in nature – in other words, attention works not by directly amplifying a specific stimulus, but by inhibiting, or blocking, other stimuli that are not related to the task at hand (Neumann and Deschepper, 1992). The capacity to dampen some cognitive activity while supporting other activity is critical to cognitive functioning; without it, cognitive activity would be like a runaway train and our thoughts would be incoherent.

Directed attention relies on a global inhibition mechanism (a general dampening of brain activity that is maintained primarily by the prefrontal cortex and anterior cingulate cortex) and is used to focus on stimuli or tasks that are important but not inherently interesting (Kandel, et al., 2012; Posner and Fan, 2001). In our modern world, we use directed attention a great deal to focus both on external stimuli (spaceflight examples include communication with ground control, routine

maintenance, attending to monitoring instruments) and also to focus on internal stimuli (for example, an idea we are working to formulate or plans we are trying making).

Involuntary attention, on the other hand, relies on local inhibition instigated by a specific stimulus that is coded as important either through learning (e.g., one's own name) or through evolutionary significance (e.g., fire, water). This local form of inhibition is highly adaptive as it allows potentially important stimuli to interrupt directed attention. The degree to which these stimuli grab attention varies and is probably related to the associated need for action in an evolutionary sense (e.g., fire, snakes, blood, sudden noise, and quick movement are strong attention grabbers, while nature and water evoke a softer form of involuntary attention) (James, 1892; Lakoff, 1987; Kaplan, 1978).

An important characteristic of directed attention is that it is susceptible to fatigue through overuse. More specifically, the inhibitory chemicals released by the parts of the brain responsible for directed attention can become depleted (Posner and Fan, 2001; Posner, 1995; Posner, 1999). As directed attention fatigues, it becomes more difficult to cut out distractions and force oneself to attend to the task at hand. This condition is termed *directed attention fatigue* (DAF) (Kaplan and Kaplan, 1989; Kaplan, 1995). The local inhibitory mechanism associated with involuntary attention is not susceptible to fatigue in the same way. Because directed and involuntary attention operate in tandem, the more one can draw on involuntary attention to complete a task (e.g., capitalizing on inherent or learned interest), the less use of directed attention will be required and the less mentally draining the task will be. So, for example, interesting work, while still requiring some directed attention, will be easier to focus on and less fatiguing than would inherently boring or monotonous work (Berman and Kaplan, 2010).

Unfortunately, in our modern day society there is often no longer a match between what is important and what is inherently interesting and we must call upon directed attention to a much greater extent than we did in our evolutionary history. Many of our modern day occupations are directed attention intense and the urban environments in which many of us live require vigilance, are full of distractions, and may be lacking restorative elements, such as nature, that tend to sooth the mind. The spaceflight environment and other ICE environments are extreme examples of environments that both require a great deal of directed attention and are extremely low in stimuli that engage involuntary attention.

The short term consequences of DAF are what one would expect – increasing difficulty in focusing on the task at hand, increasing errors, and a general decline in productivity – and are normally reversed by resting directed attention during breaks from activity and normal sleep (Lezak, 1991; James, 1892). Chronic overuse of directed attention, however, can result in a more pervasive and severe mental fatigue that cannot be addressed through sleep alone. Symptoms of a chronic or deep level of DAF include not only decreased focus, but also increased irritability, distractibility, forgetfulness, impatience, and physiological stress (Kaplan and Kaplan, 1989; Lezak, 1991; Cimprich and Ronis, 2003). People with pervasive DAF also tend to perform less well on a range of mental activities such as learning, short term memory, and problem solving (Tennesen and Cimprich, 1995; Lezak, 1991; Jonides et al., 2008) and may be more prone to risky or violent behavior as they are less able to inhibit impulses (Kuo and Sullivan, 2001).

It is important to note that DAF is not a psychological illness, personality trait, nor sign of weakness. It is simply fatigue caused by overuse of a specific neural system (the global inhibitory system), much as muscles become fatigued through prolonged use. Although there is individual variability in directed attention capacity (Posner and Fan, 2001), everyone is susceptible to DAF even though they may not be good at recognizing it in themselves.

Humans as social animals

In parallel with our evolving information processing skills, was an increasing reliance on social groups. For example, the ability to invent tools, predict animal behavior, and find one's way around large territories was essential for hunting, but successful hunting of large game could only be achieved in groups and required complex systems of cooperation and communication. Likewise, groups had clear advantages over individuals in terms of defense and gathering food. Because humans survived better in groups, evolution selected for social attachments and social behavior (Midgley, 1978; Goleman, 2006).

Just as informational needs are mediated by pleasure centers in the brain, so are our social needs. The release of oxytocin in the brain that is caused by both physical and interpersonal contact with other people (e.g., hugs, embraces, meaningful conversation) is experienced as pleasurable, so that connecting with people and being part of a group feels good (Goleman, 2006; Wickelgren, 2012). Conversely, loneliness, alienation, and lack of social support are experienced as painful and can have profound psychological and behavioral consequences, including depression, paranoia, and anti-social behavior (Salam, 2010; Simon et al., 2011; Harlow et al., 1964; Hawkley and Cacioppo, 2010).

Social connections (or the lack thereof) have a direct effect on psychological well-being, but people can also be impacted by the characteristics of the social environment in which they function. People have similar needs with respect to the social environment as they do for their physical environments – in particular, the dual needs for understanding and exploration (Kaplan and Kaplan, 1982). In a social context, understanding can be conceived as predictability. We are most comfortable in a group when we understand roles and relationships and are able to interpret and predict the behavior of others. One of the important functions of culture, in fact, is to foster understanding and predictability in social groups (Campbell, 1975). On the other hand, we have a competing need for social exploration – either through meeting and interacting with new people, learning new things about the people we already know, or meaningful participation in social activity. Social groups that are highly familiar and social contexts in which we feel there is nothing new to learn (e.g., as might be the case in socially monotonous spaceflight environments) can become boring. And environments where there is little possibility of meaningful participation (e.g., where one is not listened to or has no meaningful role to play) can become frustrating and leave one feeling alienated.

Managing the social environment. Although social interaction is critical to human well-being, the social environment can also be a significant source of stress, particularly when the environment requires vigilance against danger or unpredictable behavior, when the interactions are constrained or accompanied by different expectations, or when there are too many interactions (Romanov et al., 1996; Monroe et al., 2009; Finch et al., 1999). This last factor is implicated in sense of crowding, which is dependent not only on density, but on the number of human interactions, how people are situated in the environment, the degree of control over one's

interactions with other people, expectations of how many people there should be, one's purpose, and the amount of time one expects to spend in the environment (Insen and Lindgren, 1978; Altman, 1975; Baum and Epstein, 1978).

Functioning in stressful social environments can require a great deal of directed attention. People may need to be aware not only of what they are doing, but of how what they are doing might be perceived by others in the group. Social interaction sometimes requires inhibiting one's impulses (e.g., resisting the temptation to react out of anger) and willfully ignoring distracting or annoying habits of others. Given the need for directed attention in social situations, it is easy to see both how one might suffer from DAF through constant interactions with stressful individuals or groups and how DAF can, in turn, exacerbate social tension and disharmony. (Kuo and Sullivan, 2001; Milgram, 1970)

So although social interaction is a primal human need (Baumeister and Leary, 1995), our informational needs and limitations require that social interactions be managed. The territorial nature of humans is one mechanism for controlling social interactions at the group level. Although territoriality is often decried as a negative trait, maintaining and protecting one's territory has a number of advantages for information-based social animals. In addition to helping ensure access to resources, having a territory means having an environment that makes sense – that confers the comfort that comes with the familiar and predictable, with knowing who belongs and knowing your own place within the group (Sommer, 1977).

At an individual level, seeking privacy and removing oneself from the social group can be an extremely effective way of coping with the cognitive demands of dealing with other people. Although the need for privacy varies among different cultures and individuals, all people need a place where they can avoid distraction, let down their guard, and recharge (Stuster, 1996 and 2000). The more stressful the environment or social situation, the stronger the need for periodic privacy. Privacy is particularly important in environments, such as ICE environments, to which a group is confined for a significant period of time.

When one experiences social stress and is unable to mitigate that stress through mechanisms such as maintaining a defensible space and seeking privacy, the consequences can be severe. Lack of defensible space and defined territories in public housing projects, for example, have been cited as a primary reason for the breakdown of community and the downward-spiral of social problems found in those places as compared to other residential communities of similar socio-economic level (Yancey, 1971; Newman, 1972). At the individual level, the impacts of a lack of privacy can include lower mood, decreased helpfulness, and increased aggression (Connors et al., 1986; Ashcraft and Scheflen 1976; Altmann, 1979; Gallagher, 1993).

People-Appropriate Environments

A basic premise of environmental psychology is that people are more likely to function well, behave appropriately, and enjoy happiness and well-being in environments that address and support their needs. Obviously, environments must meet basic physical needs for food, water, sleep, temperature, and air quality. Meeting other, less immediate, physical needs – for example for light and mobility – is also important.

But beyond these physical needs, meeting psychological needs is critical. Specifically, as we've seen above, humans have explicit informational and social needs and if these needs are not met, the consequences, over time, can be dire. Environments that are high in compatibility from an information-processing approach are those with both an absence of stressors and the presence of content and patterns that support understanding, exploration, and mental restoration. We can briefly characterize these environments as:

- Rich in meaningful stimuli
- Low in distractions
- Legible and predictable
- Providing opportunities to use and expand knowledge
- Providing opportunities for participation and meaningful action
- Providing social support
- Allowing for defensible space (territory) and privacy
- Providing opportunities for mental restoration

Rich in meaningful stimuli

Humans evolved in an environment rich in stimuli and depend on external stimuli for the information they need and crave and, ultimately, for their psychological health and well-being (Schooler, 1984). The importance of environments rich in sensory stimuli for brain development is well established (Krech et al., 1960; Diamond et al., 1964; Renner and Rosenzweig, 1987; Kaler and Freeman, 1994). More recent research indicates that sensory deprivation (or sensory reduction and monotony, as found in the spaceflight environment) can cause negative changes in brain physiology even in the developed brain (Otto, 2007) and that cognitive stimulation is important throughout life in order to maintain optimal functioning (Fratiglioni et al., 2004).

Our need for sensory stimulation is expressed through environmental preferences. A considerable amount of research in environmental psychology shows that people prefer viewing and being in complex scenes and environments (i.e., those rich in information) considerably more than environments where there is less going on. At the same time, however, there is a strong preference for coherent environments, where the information is not just plentiful, but makes sense (for a review of environmental preference, see Kaplan and Kaplan, 1989). This preference for environments rich in coherent meaningful stimuli is, presumably, an adaptive mechanism for guiding us towards environments and situations where information-based organisms can thrive (Kaplan and Kaplan, 1982). And as one would expect from this evolutionary perspective, environments that lack adequate stimulation or where the stimulation is random rather than meaningful are both low in preference and not conducive to psychological well-being (for a review, see Kaplan and Kaplan, 1989).

Low in distractions

The mentally fatiguing phenomenon of information overload is a matter not necessarily of too much information, but of too much distracting or competing information. A walk in the woods will expose one to a vast amount of stimuli for all the senses, but it would hardly lead to information overload. The immense amount of distracting and competing stimuli one encounters in a crowded shopping mall, on the other hand, could certainly lead to a feeling of information overload. The amount of stimuli is not necessarily the issue; it is the relevance and coherence of the stimuli that are important. Environments that are rich in meaningful and relevant stimuli yet low in distracting stimuli (those that draw one's attention but do not fit with one's purpose) are high in understandability and thus have greater human-environment compatibility.

Legible and predictable

For an organism that depends on information, being lost or unable to predict what might happen in a particular environment or context is particularly painful. Preference studies show that legibility (being able to understand an environment and find one's way around) is a strong predictor of preference (Kaplan and Kaplan 1989; Herzog and Kropscott, 2004). Low legibility in a physical environment is related to the layout and pattern of the environment and can cause problems with wayfinding. Low legibility in a more conceptual environment, such as the domain of one's work, can be caused by not having enough information about the big picture and where one fits in. In a social context, low legibility can be related to not understanding the culture or social dynamics or to an unpredictable individual or group of individuals. With good reason, people tend to avoid situations where the chance of getting lost is high or for which they do not have sufficient information to make predictions. When they do have to function in these environments, the cognitive toll (e.g., mental fatigue or, in extreme cases, learned helplessness) can be high (Seligman, 1975). Increasing legibility can be accomplished both through environmental design and by assisting people in building appropriate mental models (Kaplan and Kaplan, 1982).

Opportunities to use and expand knowledge

The quest to display and gain competence is hugely motivating (White, 1959), as it should be for a knowledge-based species. Research from work environments show that a mismatch between the abilities and skills of a person and the demands of their work environment can generate stress. A poor fit can occur when skills are not sufficient to meet demands (leading to a feeling of incompetence) or when the demands are below one's skills and abilities (leading to boredom and apathy) (Lawton, 1980; Czikszentmihalyi, 1990; Kaplan, 1983). Supportive environments would provide opportunities to use one's knowledge and display competence while also providing enough challenge to keep one engaged and interested.

Opportunities for participation and meaningful action

In their Reasonable Person Model of human-environment compatibility, Kaplan and Kaplan (2009) emphasize people's need to make a difference, to be needed, and to participate with social groups in achieving common goals. Supportive environments are those in which people feel listened to, where they can contribute in a meaningful way (even if on a small scale), and where they have some control. Lack of opportunities for meaningful action and impact has negative psychological health implications (Antonovsky, 1979).

Social support

As social animals, psychological health and well-being depends greatly on social interactions, support and feelings of belonging. In his studies of what makes people happy, Czikszentmihalyi (1990) finds that most people feel happiest in relaxed social settings such as parks and cafes. Numerous studies point out the many benefits of strong social bonds and social support (Thoits, 1995; Idler et al., 2012) and the negative psychological and behavioral consequences of social isolation and lack of support (Harlow et al., 1964; Rubin et al., 1988). Although not every environment needs to provide social support (indeed, some environments are sought out precisely in order to escape human interactions), the matrix of environments in which one operates must include positive social interaction and provide adequate social support.

Territory and privacy

The sometimes stressful aspects of social interaction can be partially managed through territoriality and privacy. Supportive environments should allow for both. Maintaining one's territory provides security, predictability, and a sense of self (Edney, 1976). Territories can be large (e.g., nations demarcated by borders) or quite small, such as a bedroom or one's desk or work space demarcated by photos or other personal items (Brown et al., 2005). Territories can also be conceptual, such as a work assignment or a well-protected idea or theory, and worker satisfaction can be increased when one feels they have responsibility and ownership over a specific task or project (Dwyer and Ganster, 1991).

Opportunities for privacy are also very important to the maintenance of psychological health. Periodic privacy is particularly important in stressful environments or social situations in order to "get away from it all," relax, and recharge (Stuster, 1996). Private spaces do not necessarily have to be large, but they do need to be accessible and predictable (e.g., a place of one's own) and provide both visual and auditory privacy (Carrère and Evans, 1994). Both territory and private spaces can be doubly comforting and helpful in maintaining psychological health if they include meaningful symbols or objects, such as photos, flags, and other memorabilia, that can help provide a sense of identity and security (Gallagher, 1993).

Opportunities for mental restoration

Maintaining cognitive clarity, ignoring distractions, inhibiting response, navigating social complexity, and staying on task can require a great deal of mental focus and effort – in other words, a strong reliance on directed attention. As we have seen, however, sooner or later the ability to direct attention becomes fatigued. Sometimes all that is needed to restore our capacity to direct attention is a break or a good night's sleep (lack of sleep is, in fact, a significant cause of DAF; Lim and Dinges, 2008). Compatible environments should allow for breaks and must support sufficient quality sleep. Other times, particularly with intense or prolonged exposure to fatiguing environments or situations, short breaks and sleep are not enough to maintain or restore directed attention, and more is needed.

DAF recovery during waking hours requires one to rest directed attention by calling on involuntary attention to help focus the mind. Involuntary attention is based on a primitive neural system that is not susceptible to fatigue. It is hardwired, automatic and effortless; the environment presents us with a stimulus, and we respond. When involuntary attention is driving the brain, the directed attention system has a chance to rest.

There are several categories of stimuli that draw on involuntary attention. One, termed *hard fascination* (Kaplan, 1995) tends to rivet our attention – to grab it and not let go. This category includes stimuli that were important for our survival in an immediate sense and include things that even babies and other animals spontaneously attend to, such as large or threatening animals, strong emotions, blood, and loud noises. It also includes things that are uniquely interesting to humans, such as stories and mysteries (Monroe and DeYoung, 1994). Although hard fascination does activate involuntary attention, allowing directed attention to rest, it leaves little room in the brain for anything else and can require a great amount of effort to break (which is why it can be so difficult to turn off the television, stop the video game, or break off from the spell of watching a road-side accident).

There are other stimuli that evoke involuntary attention but do not dominate our minds. This category of stimuli is called *soft fascination* (Kaplan, 1995; Herzog et al., 1997) and includes things such as plants, animals, other people, and pleasant music. Softly fascinating stimuli have the advantage of gently engaging one's attention and offering a soothing and pleasant experience where one can rest directed attention while at the same time leaving room in the brain for problems and troublesome thoughts to bubble to the surface where they might be processed and laid to rest (thus resulting in a reduced need to keep them under control with directed attention). Natural environments are particularly rich in elements that engage soft fascination – water, vegetation, the light in the trees, birdsong, vistas, to name just a few – and are particularly effective restorative settings. In fact, humans tend to have a need for positive contact with nature (Wilson, 1984; Kellert and Wilson, 1993) and express preference for natural environments over other types of environments (Kaplan and Kaplan, 1989).

Environments that do not provide opportunities or mental restoration are, in the long run, detrimental to cognitive, behavioral, and social functioning. A good example is the average large city. Metropolitan areas bear little resemblance to the environment in which humans evolved and the multitude of distracting and competing stimuli, the need for vigilance, complicated wayfinding, and the vast amount of social interactions can wear on directed attention, leaving many people mentally exhausted. This fatigue is, in turn, implicated not only in reduced individual functioning, but in social ills such as reduced sociability, reduced helping behavior and increased violence (Kuo and Sullivan, 2001). The good news is that even in busy urban environments, it is possible to find restorative settings and experiences such as a walk in the park (Berman et al., 2008), relaxing in a garden (Ottoson and Grahm, 2005), or a nature view out the window (Tennessen and Cimprich, 1995).

COMPATIBILITY OF SPACEFLIGHT ENVIRONMENTS

For the uninitiated, a number of things jump out when watching videos of the International Space Station (ISS) and other spaceflight environments. Once you get past the awesomeness of the view of Earth, you are struck by the extraordinary monotony of the environment, the visual confusion of cargo and capsule innards, the cramped quarters, the repetitive and structured nature of the day-to-day work, and the difficulty of everyday tasks that we take for granted like eating, orienting oneself, or turning a screwdriver. As you glimpse the view out the window, you also realize just how far away the crew is from the people and places they hold dear. If one were to purposefully design an environment that worked against human information processing and social needs, this would be a good start.

The Informational Environment: Stimulus Poor and Distraction Rich

Space capsules are full of psychological stressors. To begin with, compared to Earth environments they provide a greatly reduced amount of meaningful stimuli: capsules tend to be no-frills structures that are relatively stark, monochromatic, and inflexible (Incoll, 1990). Contributing to the low overall level of stimulation is low levels of lighting (particularly compared to natural sunlight) with little variation among different areas or between night and day. Limited mobility, food choices, and sources of aroma further contribute to a sensory poor environment.

At the same time, capsule environments are high in distracting stimuli such as bags of cargo that are highly visible and must be worked around, floating dust and other debris, jumbles of tubes and wires, the constant low hum of fans and pumps, annoying habits of fellow crew members, and the constant threat of danger (Suedfeld and Steel, 2000). In addition, they are relatively low in legibility, due in part to the low differentiation of spaces and corridors and in part due to the problems in orientation inherent in micro-gravity environments (Lebedev, 1988; Bluth and Helppie, 1986). Although crew members quickly learn their way around, operating in environments with low legibility requires some constant level of directed attention.

The Work Environment: Challenge, Control, and Boredom

In terms of opportunities for competence, challenge and meaningful work, the spaceflight environment is mixed. For many astronauts, spaceflight is a peak life experience and has significant positive psychological benefits, including pride in challenging oneself and completing an extreme mission, participation in larger societal goals, and experiencing the grandeur of the space environment (Suedfeld and Steel, 2000). The day-to-day experience, however, may not be so positive. Much of the work in space habitats is repetitive and not particularly mentally challenging or engaging. At times there is too much work, leading to negative reactions among crew members (Maugh, 1987), and at time there is too little work, leading to boredom (Simon et al., 2011). In addition, space missions are generally heavily prescribed, and the lack of crew involvement and control with respect to daily activities and work schedules can lead to negative reactions (Seudfeld and Steel, 2000; Simon et al, 2011).

The Social Environment: Isolation, Monotony, and Lack of Privacy

From a social perspective, the spaceflight environment is the worst of both worlds. On the one hand, crew members experience social isolation and monotony – the crew is far from friends, loved ones, and traditional social support networks and instead are stuck with the same small group of people (in the range of 2-6, Vakoch, 2011) for prolonged periods of time. On the other hand, despite the isolation and limited number of personnel, the environment may feel crowded, as the small confined quarters and the nature of the work demand constant social interaction with other crew members. In addition, there are limited opportunities for the privacy that one needs to escape these interactions (Simon et al., 2011).

The negative effects of isolation are exacerbated by the knowledge that one cannot choose to leave the environment and that rescue would be difficult or impossible (Bishop, 2011). The social environment in a longer-duration spaceflight (e.g, a mission to Mars) will be even more extreme as there will be long delays in communication and thus reduced access to both psychological and decision making support from Earth.

Opportunities for Mental Restoration: Lack of Soft Fascination and Difficulty in Getting Away from it All

Relatively few opportunities exist in spaceflight environments for mental restoration, as the environment is lacking in stimuli that evoke involuntary attention, particularly through soft fascination (e.g., nature elements). In addition, sleep, the most effective way to restore one's directed attention capacity, is often disturbed in space and other extreme environments because of disturbed day/night cycles, general stress, noise, temperature, and difficulties in getting comfortable in micro-gravity (Mullin and Connery, 1959; Myasnikov and Zamaletdinov, 1996; Suedfeld and Steel, 2000).

Some of the activities that are enjoyed in ICE environments do provide opportunities for restoration, although many simultaneously use both involuntary attention and directed attention (e.g., reading, photography, self-education) or rely primarily on hard fascination (e.g., television, movies, or video games). Although these activities are very important for entertainment, mental engagement and stimulation, and periodic escape, they may not be particularly effective in terms of the recovery of directed attention capacity.

CONSEQUENCES OF PERSON ENVIRONMENT INCOMPATIBILITY IN THE CONTEXT OF SPACEFLIGHT

The reality of spaceflight environments (and indeed, of many ICE environments) means that they do not fare well when viewed through the lens of human environment compatibility. What are the consequences of functioning in an environment with low compatibility? Initially, there may be few visible costs. In fact, rising to the challenge of an extreme environment can have some positive psychological effects and evoke extraordinary levels of morale and cooperation (Gallagher, 1993; Palinkas, 2000). In the short term, people are remarkably adaptive and often cope surprising well with unsupportive environments and environmental stressors (Suedfeld, 1987). They may be so adept, in fact, that one may assume there are no costs associated with coping. Compounding the problem is that many of the costs of coping do not appear at the time

of the stressor (Cohen et al., 1986); rather, they happen gradually and are often only apparent after major damage has been done.

Whether one sees it coming or not, however, there are consequences of coping with environmental stressors – both those stressors that come from the external environment (e.g., noise, poor lighting, temperature extremes, distractions, social interactions) and those that come from inside the head (e.g., dealing with too many things at once, boredom, uncertainty, lack of involvement, painful thoughts that need to be suppressed). Some of the costs of coping are immediate, such as increased perspiration and high heart rate; others are low level and chronic, such as headaches, mental fatigue, depression, and other psychological and physical ailments.

Stress and Coping

It is useful to distinguish between environmental stressors and stress. The term "environmental stressor" is used to describe an incompatible or unsupportive stimulus or environmental characteristic. Stress, on the other hand, is a physiological response to a stimulus or event that is perceived as threatening or harmful. Stress prepares one for action – for fight or flight. From an evolutionary perspective, this response is, of course, adaptive as it increases one's ability to deal with immediate threats. Unfortunately, in our modern world, we are constantly subjected to environmental stressors for which neither fight nor flight are appropriate responses. Prolonged exposure to these stressors lead to chronic levels of elevated stress hormones which have serious consequences, including problems with memory formation and retrieval, increased anxiety, withdrawal and, in severe cases, post-traumatic stress disorder (Arias and Otto, 2011; McEwen and Sapolsky, 1995; Ehlers and Clark, 2000). Stress is also implicated in a host of physical diseases, such as heart disease (Quick et al., 1987).

There are environmental stressors, however, that do not necessarily induce a strong physiological stress response. Some of the environments and stimuli that contribute to DAF fall into this category. Navigating a complicated urban environment, managing one's own behavior in a social setting, and ignoring distractions while trying to get one's work done may not evoke significant physiological stress responses, but the mental energy expended in coping in these contexts can still leave one feeling "stressed out" and can have serious psychological and behavioral consequences. The differentiation between stress in the physiological sense and stress in the general sense is important to keep in mind in terms of assessing environmental compatibility and effective countermeasures for environmental stressors as studies that solely focus on physiological stress will likely miss much.

Impacts of Sensory Deprivation and Distraction

An astronomy researcher who wintered-over in Antarctica commented that in terms of sensory information the experience was, "Kind of like not leaving your house for a year. After a while, so much of your environment is the same, it feels like part of your brain shuts down" (McKee, 2000). Research on the effects of sensory deprivation supports the notion that the brain can be severely impacted by a lack of stimulation (for reviews, see Arias and Otto, 2011 and Daffner, 2010). At the structural level, sensory deprivation has been linked with physiological changes in the brain; for example, reductions in synaptic connections, changes in brain chemistry, and atrophy of those areas of the brain receiving reduced sensory stimulation (Fan et al., 2007; Connor et al., 1981; Kempermann et al., 1997; Arias and Otto, 2011). These physiological

changes can have negative effects on memory, spatial orientation, sensory perception, and other aspects of cognitive functioning (Zinger et al., 2001; Zubeck, 1973).

At the psychological and behavioral levels, sensory deprivation in controlled laboratory settings has resulted in decreased ability to concentrate, deficits is task performance, anxiety, decreases in verbal fluency, and disorientation (Heron, 1961; Vernon, 1963; Rasmussen, 1973; Hebb, 1980). Sensory deprivation can also shift the primary driver of cognitive activity from external to internal stimulation. As we've seen, this can be beneficial if the internal stimuli (thoughts, ideas, plans) are what one would like to focus on. On the other hand, leaving the running of the brain solely to internal stimuli can blur the line between what is in the mind and what is in reality and can lead to hypochondria, psychosomatic problems, and hallucinations (Gallagher, 1993; Suedfeld and Mocellin, 1987).

One must exercise some caution in extrapolating from laboratory sensory deprivation experiments to ICE environments as these conditions differ enormously in terms of subjects, level of deprivation, and deprivation duration (Suedfeld, 1991). Direct evidence from ICE environments indicates, however, that sensory deprivation (or, more accurately sensory reduction and monotony) is indeed a significant psychological health risk (for reviews of this literature, see Arias and Otto, 2011; Simon et al., 2011; Vakoch, 2011; Suedfeld and Steel, 2000). Russian cosmonauts report a "sensory hunger" that results from insufficient sensory stimulation during space missions (Parin et al., 1972/74) and analysis of astronaut journals indicates that sensory deprivation can impact overall well-being (Stuster, 2010). People in other ICE environments, such as Antarctic research stations and submarines, have similarly experienced negative symptoms. Particularly vivid are the consequences of extended periods of sensory deprivation and solitary confinement in prisons, where inmates have experienced spatial and temporal disorientation, extreme anxiety, hallucinations, difficultly with memory and concentration, and other negative psychological and behavioral symptoms (Haney, 2003; Grassian, 1983; Anderson et al., 2000; Gendreau et al., 1972; Haney and Lynch, 1997).

The effects of sensory deprivation can be worst when it is not total deprivation, but rather sensory monotony. As Suedfeld (1991) points out, Hebb's original experiments in sensory deprivation actually used monotonous and constant moderate levels of noise and light. The negative outcomes of these experiments were considerably more severe than later experiments which used no external stimulation. Similarly, constant exposure to the monotonous noise in space capsules contributes to irritability, sleep disorders, and headaches (Bluth and Helppie, 1986). Although this background noise may not reach levels high enough to damage ear structures, it is distracting, makes purposeful behavior more fatiguing and can impair concentration and performance (Jahncke et al., 2011; Poynter, 2006). Adding to the distracting nature of background noise in space capsules, is that fact that astronauts tend to unconsciously listen to the noise to see if the station is functioning correctly. Although this unconscious listening may be an operational necessity (i.e., in order to monitor the spacecraft for correct functioning) it is nevertheless mentally fatiguing.

Also distracting is the amount of visual clutter in the space capsule environment (e.g., ducts, tubes, stowage). Disorganized stowage is particularly problematic – it not only poses a visual distraction but inefficient organization makes finding necessary tools and supplies time consuming and frustrating. As one ISS astronaut wrote, "Spent the entire morning unpacking. I

am starting to get irritated at the stowage plan. Every time I unpack a bag, I have to stow the empty bag somewhere (they are only semi collapsible). I am now getting overwhelmed by bags. The airlock is a disaster area; I have attempted to keep it orderly since I've been here, but it's simply swamped with the volume of stuff we've thrown into it. Every light is blocked, so working in there is like spelunking. I'm not sure where the ISS designers figured we were going to put all this stuff" (Stuster, 2010, p. 37).

The relatively low light level in capsule environments is not a distraction in the traditional sense, but it does increase the need for directed attention in getting work done. Having adequate light levels in work environments is associated with both productivity and worker satisfaction (Vischer, 2007; Thayer et al., 2010; Sundstrom, 1986). The same is true in spaceflight environments: A simulated flight experiment showed that although subjects were initially satisfied with a minimal level of illumination, they required increased lighting as mental fatigue (generated through both intense visual work and working with background noise) set in (Bluth and Helppie, 1986). Similarly, cosmonauts are known to want more light as the time in space increases (Bluth and Helppie, 1986).

Lack of light, specifically of sunlight, may also have direct effects on mood and health. The function of light in maintaining circadian rhythms is well established (Brainard et al., 2001; Roberts et al., 2000; Veitch et al., 2004) and lack of sunlight is implicated in a range of health problems, including insomnia and mood disorders such as seasonal affective disorder (SAD) (Stevens et al., 2007; Rea et al., 2008; Arendt et al., 2008; Brainard et al., 2001). A twelve month study of a group wintering over in Antarctica showed that insomnia was more widespread during the winter season (with its 24 hours of darkness) than during the summer season (with its 24 hours of daylight) (Mullin and Connery, 1959). Other researchers have found changes in thyroid function during the winter among a wintering-over Antarctic crew (Gold et al., 1981; Palinkas et al., 1997); these changes are associated with increased depression and decreases in cognitive functioning (Gold et al., 1981; Palinkas et al., 1997). The lack of sunlight during winter-overs can not only cause insomnia, but can affect sleep quality when sleep finally does come. For example, studies of Antarctic winter-over crew have used brain wave tracings to show that Stage IV sleep (one of two periods of restorative "deep sleep" in which brain activity slows down) tends to disappear over the winter (Palinkas, 2000).

Although lack of sunlight and changes in light cycles can significantly impair sleep, problems with insomnia and poor quality sleep in ICE environments are also a function of general stress. Several studies report that stress is a leading cause of insomnia (Williams et al., 2011; Jansson and Linton, 2006; Knudsen et al., 2007; Linton, 2004) and thinking or worrying about the mission has been found to be a significant factor in falling and staying asleep in spaceflight (Whitmire et al., 2011).

Impacts of Workload Incompatibility

Excessive workloads during space missions can lead to mental fatigue, anxiety, and tension between crew and ground control (Levine, 1991; Brady and Anderson, 1991; Pogue, 1974). In one example, midway through their mission a Skylab crew went on strike and took an unscheduled day off work (Maugh, 1987). This was a relatively extreme reaction in an organization that emphasizes and selects for adherence to rules and protocol. The reaction should not have been completely unexpected, however, as there is ample evidence that working too many hours has negative effects. A study of British civil servants, for example, showed that working over 55 hours per week (as compared to 40 hours or less) was associated with lower cognitive functioning (specifically short term memory, semantic fluency, and reasoning skills) and that functioning continued to decrease as working hours increased (Virtanen et al., 2009). A follow-up study showed a relationship between working long hours and major depressive episodes (Virtanen et al., 2011).

Adding to the problem of overwork is lack of crew control over when and how they work (Cooper, 1976). To date, all space missions have been under virtually continuous control by ground command and crew work is heavily scheduled and programmed (Brady and Anderson, 1991). Micromanaging by ground personnel is one way to control the mission, but it has the unintended consequence of leaving crew members with a loss of control and autonomy. Lack of control in work and residential environments can be a major source of stress, impacting mood and performance (Sherrod, 1974; Cohen and Sherrod, 1978; Baum et al, 1981; Hickson and Stachs, 1985) and leading to tantrums, frustration, conflict between crew and ground personnel, demoralization, and, in extreme examples, violence (Kaplan, 2009; Lebedev, 1988; Palinkas 2001).

Of course, not all work is negative. In fact, being engaged in meaningful work is critical to psychological well-being (Vischer, 2007; Eberhard and Hooper, 1970). In the context of a physical environment with little else to do, having meaningful work takes on extra importance. In the spaceflight environment, having engaging and meaningful work is a critical factor in adjusting to life in space and in maintaining psychological well-being (Stuster, 2010; Lebedinskiy, 1964). The same is true in other ICE environments. A study of thirty-nine wintering over members of an Antarctic crew, for example, found that the personnel who fared best were those who were occupied with activities of a high special interest to them (Mullin and Connery, 1959). A key factor in workload is the ratio of mentally engaging work to tedious and routine work. Psychological health is improved when a substantial amount of the work is related to important goals rather than routine station keeping (Stuster, 2010; Bishop, 2011). As one astronaut on the ISS wrote, "Busy work also causes me to miss home more. I think I feel less of a sense of purpose if I don't believe in the tasks that I am doing. Of course, I will continue to do them and to press on. But, it does make the days go longer" (Stuster, 2010, p. 11).

A hallmark of activity during spaceflight is its inconsistency – although there is a great deal of prescribed work, there are also long stretches of time where there is not much to do (Connors et al., 1985). This unstructured time can provide an opportunity to recover from the stresses of work, but it is often a stressor in and of itself. The prolonged periods of down time, combined with work that is repetitive and not particularly engaging, can lead to boredom – this is a particular problem in the stimulus poor spaceflight environment where there is little in the

physical environment to stimulate the mind (Bluth, 1981; Gurovskiy et al., 1980; Suedfeld and Steel, 2000). For an organism that is driven to seek challenge, a state of boredom in not only mentally painful, it can also lead to risky behavior in the search for challenge and engagement. As Arias and Otto (2011) point out, a number of accidental deaths and injuries have occurred in the Antarctic as a result of "enui-bred adventurism," such as the bored British scientists who died in 1982 while exploring a forbidden Antarctic area. A less dramatic example of inappropriate behavior is the total disregard for rules as members of the second Biosphere 2 crew sought relief from the monotony of the biospherian diet by smuggling in special treats (Poynter, 2006).

Impacts of Social Isolation and Monotony

Social isolation is a significant source of stress in ICE environments (McGuire and Tolchin, 1961; Mullin and Connery, 1959; Suedfeld and Steel, 2000). For an organism that is so highly social, the consequences of social isolation can be particularly dramatic. The devastating effects of social isolation during infancy and childhood has been clearly demonstrated (Harlow et al., 1964; Rubin et al., 1988) and other studies point to the continued important of social connection throughout one's life (Idler et al., 2012; House et al., 1988). Lack of social support in ICE environments has been associated with anxiety, depression, and a reduced ability to cope with other stressors (Bachman and Otto, 2011; Suedfeld and Steel, 2000).

Social monotony and forced interactions are also significant stressors in ICE environments. Nowhere has this been more apparent than in Biosphere 2. Despite the stimulus rich environment, the combination of social isolation and monotony, coupled with a lack of psychological support services, led to an almost total breakdown of social functioning by ten months into the mission and palpable hostility for the duration of the mission (Poynter, 2006). Compounding the problem was the fact that crew members were constantly on stage. As biospherian, Jane Poynter, writes, "From nine every morning to five at night, there was rarely a moment when I could not look up and see tens – if not hundreds – of visitors outside, many of them pointing fingers or cameras at me or other biospherians they spotted" (Poynter, 2006 p. 142). The only thing that kept many of the biospherians sane was the ability to communicate with loves ones and others outside the crew of eight.

Although there are few examples as extreme as Biosphere 2, interpersonal problems are common in other ICE environments, and can lead to loneliness, anxiety, paranoia, withdrawal; depression, and violence (Cacioppo and Patrick, 2008; Macpherson, 1977; Stuster, 1996; Bluth and Helppie, 1986; Suedfeld and Steel, 2000). These problems, if not addressed, are likely to escalate over time and are thus of particular concern during long-duration missions. In a poignant example, Valentin Lebedev (1988) describes how by the end of his 211 day space mission, he and his good friend and fellow cosmonaut (the only other person on the mission) were almost completely alienated, avoiding talking to one another and keeping to opposite ends of the capsule. Interpersonal problems are exacerbated when crew members lack private space where they can be alone, control social interactions, and mentally restore themselves from the environment's many stressors. (Simon et al., 2011; Stuster, 1996).

Directed Attention Fatigue, Asthenia, and Winter Over Syndrome: Impacts of Lack of Opportunities for Mental Restoration and Stress Reduction

Lack of sensory stimulation, problems with the work environment, and social isolation – all coupled with the extreme DAF that can result from coping with these environmental stressors – have serious psychological and behavioral consequences. Studies of Antarctic winter-overs find significant problems with absentmindedness, poor concentration, wandering of attention, and lapses in memory (Mullin, 1960; Mullin and Connery, 1959; Barabasz, 1991). In a number of cases, the impairment has been more extreme, taking the form of a mild "fugue" state where crew members do not appear to be completely present (Mullin and Connery, 1959). As one crew member said, "I laugh at myself and say that my attention span must be equivalent to that of a kindergartner. Both my recent and remote memory is lacking. I sometimes forget simple vocabulary words that I have known for perhaps twenty years. Or, I walk to get something and forget what it is two seconds later" (Oliver, 1991, p. 225).

These cognitive impairments, coupled with sleep disturbances, depression, and irritability, have been termed "winter over syndrome" because of their prevalence among Antarctic winter-over crews (Palinkas and Browner, 1995; Strange and Klein, 1973). Although the etiology of winter over syndrome is not clear, it has been attributed to social isolation, increased work demands, and lack of opportunity to disengage from stressful situations (Palinkas et al, 2001).

Similar to winter over syndrome is "asthenia," which is the name given to a constellation of symptoms experienced by spaceflight crew members, including reduced working capacity, fatigue, sleep disturbance, decreased efficiency, inability to concentrate, irritability, forgetfulness, headaches, and changes in neurology (Kanas et al., 2001; Lebedinskiy, et al., 1964; Aleksandrovskiy, 1976 as cited in Kanas et al., 2001). The syndrome has been of particular interest to Russian researchers. Research and observation support the notion that at least a mild form of asthenia develops in many cosmonauts after one to two months of flight (Aleksandrovskiy and Noviekov, 1996 as cited in Kanas et al., 2001) and that more severe forms are common in missions of over four months duration (Myasnikov and Zamaletdinov, 1996 as cited in Kanas et al., 2001). As asthenia moves from its mild to more severe form, the decreased attention and concentration, sleep disturbance, and emotional instability give way to more severe fatigue, and finally to constant fatigue, indifference, passiveness, and lack of work capability (Aleksandrovskiy, 1976 as cited in Kanas et al., 2001) Inevitability, these effects on the individual are implicated in crew conflict (Myasnikov and Zamaletdinov, 1996 as cited in Kanas et al., 2001).

The overlap of winter-over syndrome and asthenia symptoms indicates that, although perhaps not identical, they are likely similar. Furthermore, the similarity of these syndromes with the symptoms of chronic mental fatigue suggests that DAF, coupled with a lack of opportunities to mentally restore oneself, plays a significant role in both of these syndromes. Also implicated in winter-over syndrome and asthenia are the neurophysiological and neurochemical changes that can result from long periods of sensory deprivation or monotony, from lack of exposure to normal night/day cycles and full spectrum sunlight, and (in the case of spaceflight) from extended exposure to microgravity (Palinkas et al., 1996, Valzelli, 1973; Miller et al., 1989).

The notion that the symptoms of winter over syndrome and asthenia are due to chronic underlying conditions, such chronic DAF, chronic stress, and neural changes brought about by sensory deprivation, is supported by the fact that the symptoms can last long beyond one's exposure to environmental stressors (the decrements associated with both DAF and neural changes tend to persist if left unaddressed (Berman and Kaplan, 2010; Seidler, 2012)). Lebedinskiy (1964) reports that in one study, symptoms of asthenia lasted for two months after only sixty days in a simulated space capsule environment. He concludes that this was perhaps because, "[The] adaptive capacities of the organisms themselves have been weakened by the prolonged influence of unfavorable factors in the course of the tests" (p. 7). Several studies of Antarctic winter-over personnel show a similar longevity of negative symptoms (Harrison et al., 1991). In some cases, negative psychological and cognitive effects are extreme, long lived, and difficult to treat as is the case with the post-traumatic stress disorders experienced by some individuals after long-duration experiences in ICE environments (e.g., Poynter, 2006).

In the spaceflight environment, the consequences of DAF can not only impair the psychological health of the individual, but can have significant implications for group conflict, work efficiency and accuracy, and communication with ground control. As levels of DAF increase, one's ability to complete tasks requiring concentration diminishes (Kaplan and Kaplan, 1982; Tennesen and Cimprich, 1995; Jonides et al., 2008), meaning both that more time must be spent on task completion and that the probability of errors increases. In addition, because cognitive processes involving executive control (e.g., planning, decision making) require directed attention, these processes are also compromised (Lezak, 1982). Finally, individuals suffering from DAF are less able to inhibit responses, meaning that they tend to be less 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). Although DAF has not been directly studied in space or other ICE environments, observed problems with mental fatigue, work productivity, and inter-personal conflict indicate that it is a significant factor. Some of the journal entries from ISS astronauts (Stuster, 2010) provide a glimpse of the effects of DAF:

> *The fatigue was evident when a couple of minor mistakes were made today on some payload activities. The ground caught the mistake and helped me out. But it is an obvious indicator of fatigue (p.13.)*
>
> *As the time goes on, my natural inhibition against lashing out on the radio about something that isn't going right for various reasons is noticeably reduced. I need to be careful, because I know very well that I can undo a good reputation with a single misplaced or inappropriate sentence (p. 15).*
>
> *We did have a run-in one night. I was really livid after Z snapped at me quite viciously about something that wasn't my fault. I let Z have it, like I can't remember ever before in a professional relationship, and stormed off (p. 22).*
>
> *I'm finding myself losing tolerance for T. I can't explain exactly what it is that bothers me (p.22).*

Implications for Longer-Duration Spaceflights

Although one must be cautious in generalizing from data on short and medium term missions in ICE environments to longer term missions, there is enough data to suggest that the risk of negative psychological, social, and behavioral effects becomes greater as mission duration increases (Baum et al., 1981; Kublis, 1972; Aleksandrovskiy, 1976 in Kanas et al., 2011). Certainly, there is evidence that DAF can become chronic, severe, and more difficult to treat when there is continued exposure to environmental stressors coupled with lack of opportunity for mental restoration (Kuo and Sullivan, 2001; Cimprich, 1993; Kaplan, 1978). In his analysis of astronaut journal entries logged throughout long-duration ISS missions, Stuster (2010) found that although the physical demands of being in space got progressively easier as crew gradually adapted to conditions, mental difficulties and organizational problems did not diminish. In fact, the number of interpersonal problems increased by 20% in the second halves of the missions. Similar evidence comes from studies of cosmonauts where data indicate that spaceflight personnel require more assistance in coping with environmental stressors as their own cognitive coping mechanisms are weakened and fatigued. Bluth and Helppie (1986), for example, note that cosmonauts' desire for privacy increases as mission length increases; similarly, there is a greater need for social support as mission length increases, as shown by increased depth and duration of external communication. Astronauts have similarly noted that opportunities for restoration and entertainment become increasingly important as the mission progresses (Pogue, 1974).

As Oleg Gazenko's concluded several decades ago (Oberg and Oberg, 1986), the limitations of living in space do indeed appear to be largely psychological. Jane Poynter, in her account of the failings of the first Biosphere 2 mission (2006, p. 243), similarly concludes, "Again and again as I explore what went wrong during our two year mission, I come up against the same answer – the technology was sound, the idea was noble, the project was visionary and courageous, but simple human frailty brought the walls crashing down."

MITIGATING BEHAVIORAL AND PSYCHOLOGICAL RISK FACTORS OF LONG-DURATION SPACEFLIGHT ENVIORNMENTS

Clearly, the psychological and behavioral effects of the spaceflight environment (and other ICE environments) can be debilitating, impacting mission success and having negative consequences for individuals long after the mission is completed. Lowering risk factors and ameliorating some of the consequences of environmental stressors are important considerations in spacecraft and mission design and should be considered from the very beginning. This is even more important in the context of longer-duration spaceflight (i.e., over one year), where we would expect the symptoms and consequences of environment incompatibility to increase in severity (Leon, 1999).

How can we mitigate the risk factors inherent in settings with low human-environment compatibility? One strategy is to reduce environmental stress by increasing human-environment compatibility. Because compatibility is a two way street, one could either change the environment to reduce stressors (Thayer et al., 2010) or one could change the people (e.g., through training, education, or selection) to improve their fit with the existing environment. A second strategy is to endure the mental costs of environmental stressors and recover from these

costs later in a restorative setting. Reliance on this second strategy alone is not feasible in ICE environments because of their particularly high level of environmental stressors and the fact that people are confined to these environments for extended periods of time. On the other hand, design and environmental constraints mean that environmental stress cannot be eliminated, or even reduced to an acceptable level, through environment and human engineering alone.

Therefore, in the context of spaceflight and other ICE environments, successful strategies for mitigating environmental risk will require a focus both on reducing stressors and on providing mechanisms and opportunities for recovering from the effects of stressors. Specifically, a successful risk mitigation strategy should include: (1) modification of the physical, work and social environments to reduce environmental stressors, (2) careful selection and training of spaceflight personnel to increase the capacity of the crew to cope with the spaceflight environment, and (3) development and implementation of effective countermeasures to assist crew members in coping with and recovering from the mental costs associated with environmental stressors that cannot be eliminated.

The next section explores countermeasures in detail, providing an evidence review of promising countermeasures along with specific recommendations for adapting effective countermeasures for use in long-duration spaceflight.

2. Countermeasures for Behavioral and Psychological Risk Factors during Long-Duration Spaceflight: A Review of the Literature

INTRODUCTION

Space and other isolated, confined and extreme (ICE) environments are difficult places for people to thrive. Even if the physical hardships (e.g., extreme temperatures, high radiation levels) can be addressed, the characteristics of these environments – low in sensory stimulation, socially isolated, socially monotonous, limited space, lack of privacy, and long periods with little to do – take a toll on psychological health and well-being (Vakoch, 2011; Simon et al., 2011, Suedfeld, 1991).

For as long as people have lived and explored in these environments, they have employed countermeasures for coping with the inherent hardships and stressors. Activities such as communicating with friends and loved ones, writing, playing games, reading, engaging in hobbies, watching TV and movies, exercising, and planning celebrations have long been used to maintain social support, entertain oneself, overcome boredom, and relieve some of the fatigue of monotonous environments. While virtually all these activities have value – mood enhancement, passing the time, getting away from it all – some are more effective than others at ameliorating the negative psychological consequences of confined, isolated, monotonous, and low stimulus environments.

Based on the framework of human environment compatibility in spaceflight environments developed in the previous chapter, and the specific risk factors identified, we can move beyond general leisure-time activities to identify other countermeasures that may be particularly effective in reducing environmental stressors and maintaining psychological health and well-being.

Given the extreme nature of the spaceflight environment and the potentially prolonged period of time spent in that environment, risk mitigation should be multifaceted and should be done as an integral part of capsule design and mission planning. Specifically, a comprehensive strategy of risk mitigation for spaceflight should include:

1) modification of the physical, work and social environments to reduce environmental stressors.

2) careful selection and training of spaceflight personnel to increase the capacity of the crew to cope with the spaceflight environment.

3) development and implementation of effective strategies to assist crew members in coping with and recovering from the mental costs associated with environmental stressors that cannot be eliminated.

In order to identify effective countermeasures, a broad evidence review was conducted based on space and analog studies (e.g., Antarctic research stations, prisons, military), research in work environments and residential environments, studies in environmental psychology, and other relevant studies in psychology and human behavior.

MODIFYING THE ENVIRONMENT TO REDUCE STRESS

The goals of capsule and mission design, from the point of view of psychological well-being, should be to support human needs and desired behaviors, to maximize the amount of meaningful sensory stimuli, and to eliminate or reduce environmental distractions and other stressors.

Capsule Layout and Size: Meeting Needs for Community, Work, and Privacy

One's space needs to fit one's needs and purposes. In the context of space capsules, the usable interior space must meet the simultaneous needs for community, work, recreation, and privacy (Carrère et al., 1991) and should provide, as much as possible, for physical separation of these activities. Estimates of acceptable capsule size (or space per person) vary considerably (Conners et al., 1985; Stuster, 1996), but there appears to be widespread agreement that current capsule size is insufficient, particularly for longer-duration missions (Simon et al., 2001; Suedfeld and Steel, 2000). Capsules need to be large enough to provide:

Space for socializing. The ability for the entire crew to comfortably be in the same room at the same time is important for team cohesion (Simon et al., 2011) and the capsule environment should include a sufficiently large common area.

Space for recreation. Space for both active and passive recreation is needed in the capsule environment. Exercise is the primary means of maintaining physical fitness and slowing losses of bone density and muscle. Space for exercise should be large enough so that exercise can be comfortably done without impacting other activities (e.g., work, passive recreation, and reflective activities).

Comfortable and efficient work environment. In a sense, the entire capsule is the work environment, as the crew's duties bring them to nearly every part of the capsule. However, special consideration should be given to designated work areas (e.g., work stations, computer terminals). These spaces should be separated in some manner from areas where other activities (e.g., exercise, socializing, or eating) are taking place and should be insulated from other distractions such as noise. Some studies suggest that people feel most comfortable in their workspace when the space has at least partial enclosure (particularly enclosure behind and to one side) and a view (though not a distracting one) into a larger space (Alexander et al., 1977).

Private space. A recent workshop on the requirements for space capsule size identified lack of private space as one of the top stressors for long-duration space missions (Simon et al., 2011). 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). Each crew member should have their own private space (i.e., one that is not rotated among multiple people) and, as much as possible, should have the same space for the duration of their time in the capsule (particularly for crew members completing longer stays). Private areas need to include space for comfortable sleeping, private passive recreation (e.g., reading, engagement in virtual environments), and private work (e.g., journal writing, private communication). Private spaces need to provide auditory, as well as visual, privacy and thus should be situated away from areas of higher activity, such as common spaces and spaces for active recreation (Simon et al., 2011).

Designing the Environment to do the Work: The 007 Principle

The less mental energy one needs to function in an environment, the more mental capacity there is for more important things. Reliance on the environment to provide us with useful information has been termed the "007 principle" (or "need to know" principle) by Clark (1989; clearly a James Bond fan). The principle asserts that “in general, evolved creatures will neither store nor process information in costly ways when they can use the structure of the environment and their operations upon it as a convenient stand-in for the information-processing operations concerned. That is, know only as much as you need to know to get the job done” (p. 64). For example, shops that follow a logical layout allow people to find what they need with minimal mental effort – they don't have to remember or think about where things are, the environment tells them. On the other hand, a poorly designed hospital environment, with undifferentiated corridors and wings, provides little wayfinding help and requires a great deal of mental effort to navigate – energy that could be better spend on other things.

The notion that the environment should complement and facilitate human functioning underlies much of the work in human factors research, which focuses on workspace and tool design (Proctor and Van Zandt, 2008). Having the right tools where you need them, displays and knobs that make intuitive sense, and computer interfaces that are easy to navigate make one's job less taxing, increases work efficiency, and reduces the chance of errors. These same principles can also be used in the design of the broader capsule environment, particularly with respect to orientation and helping define different spaces or activity zones.

In space, crew have no gravitational reference for orienting themselves and must instead use the details of the capsule environment to figure out where to locate a tool or in what direction to go. Unfortunately, the typical monochromatic and cluttered capsule environment provides little assistance. When space crew members are mentally fatigued or tired, the extra mental energy required for orientation may lead to errors or a reduction in performance. As Lebedev (1988) writes, "And if you need something like a camera, maps, journal or equipment, you can't immediately understand where you are, what position you're in, what is up what is down, where is what plane. So you start using the details of the compartment or the interior of the station to reorient yourself ... [sometimes] instead of going into the hatch to the station, you go into the transport vehicle hatch. Sometimes you float into the working compartment and you don't understand what it is" (p.69).

Although there is some disagreement about the importance of maintaining an "up and down" orientation (Arias and Otto, 2011), a sense of relative orientation is important for efficiency and wayfinding. Placing furniture and other fixtures in earth-normal position relative to one another is helpful with orientation, as is the placement of bulkier (perceptually heavier) items in the "down" position and perceptually lighter items in the "up" position (Bluth and Helppie, 1986; Johnson, 1975). Color is also an effective aid in orientation. Color-coding areas corresponding to walls, floors, and ceilings has proven effective in helping with orientation (Bluth and Helppie, 1986) as has using brighter and lighter colors in the "upper" visual field and darker colors in the "lower" visual field (Barbour and Coss, 1988; Oman et al., 1986).

Color, light, and other landmarks can also be effectively used to differentiate modules and activity zones within the capsule. For example, using different colors on corridors and the modules they lead to can provide an immediate reference for where one is and where one needs to go. Subdued lighting can indicate that a space is more private or quiet, while brighter lighting tends to draw people in, provide a sense of energy in a common area or active recreation area, and increase the level of social interaction and communication (Alexander et al., 1977; Gifford, 1988).

Appropriately organized and placed stowage can also significantly reduce the cognitive load on crew members. Haphazardly organized stowage is not only a visual stressor, but having to put significant effort into retrieving an item when it is need, or spending time looking for lost items (a common problem in spaceflight as items tend to float away) is a mental drain. The kindergarten model of supply stowage would be useful in capsule design: items should be stored in close proximity to where they will be used, stowage systems should be designed around behaviors (e.g., most frequently used items stored in plain sight, etc.), and finally, everything should have a home and be easy to put away and secure.

Personalization and Control

Capsule environments should be designed for at least some flexibility, as the ability to reconfigure furniture, decorate spaces, and control environmental aspects such as temperature, ventilation and lighting can facilitate crew adaptation and adjustment and provide a sense of control (Vokoch, 2011; Simon et al., 2011). In addition, space crew should be allowed and encouraged to decorate both common and private areas. Cosmonaut Valentin Lebedev (1988) writes about the importance of items from home, "Many little details, such as photographs on the panels, children's drawings, flowers, and green plants in the garden, turn this high tech complex into our warm and comfortable, if a little bit unusual, home" (p. 273).

Decorations and other items in the common area can help create a sense of team unity if they are generated by and meaningful to the crew (much as flags, pictures, and memorabilia in the locker room can provide a sense of unity in a sports team or team-relevant cartoons or inside joke items in office common space can help maintain a sense of unity among team members). Likewise, color, decoration, photographs, and other personal items in one's private space can reinforce one's sense of self and provide emotional support (Vischer, 2007; Carrère and Evans, 1994).

Increasing Meaningful Sensory Stimuli

Capsule environments need to be functional and efficient with minimal distractions. They also, however, need to be varied and interesting (Berry, 1973). As Hebb writes in his *Essay on Mind*, the data from his sensory deprivation experiments at McGill University show that "the integrity of the mind at maturity continues to depend on ... the sensory stimulation of the normal complex environment" (p.96). Several decades of research show that living in a sensory rich environment is critical for normal brain biochemistry, cognition, and behavior (for a review, see Van Praag et al., 2000). This is true not only in the developing brain, but in the mature brain as well. Even temporary changes in sensory input can result in persistent changes in the sensory and motor areas of the brain (Wang et al., 1995; Jenkins et al., 1990). Fortunately, increasing sensory stimulation can help the brain to reorganize or repair itself (Renner and Rosenzweigh, 1987), leading to cognitive and functional improvements (Hamdy et al., 1998; Kempermann et al., 1998; Collier et al., 2010), the recovery of normal sensory functions (Sale et al., 2009) and synaptic renewal and enrichment (Cotman and Sampedro, 1982; Finnerty et al., 1999).

But not all stimuli are equal when it comes to maintaining and promoting cognitive and psychological health. The many studies on the cognitive, behavioral, and neurophysiological benefits of enriched environments for rats, for example, do not use random stimulation; rather, they use environments that are sensory rich in a way that is meaningful and useful to a rat – filling the cages with tunnels, toys, running wheels, and other rats. The goal of environmental enrichment, then, is to not just to increase the amount of stimulation, but to increase the amount of *meaningful* and *relevant* stimulation.

Zookeepers have long known that many animals fail to thrive when removed from their natural environment, even when their needs are provided for in terms of food and living conditions (Depledge et al., 2011). Environmental enrichment that seeks to provide positive sensory stimuli similar to those found in the animal's natural environment has been found to eliminate aberrant patterns of behavior, increase reproductive success, increase behavioral repertoire, reduce physiological stress and generally promote animal health and well-being (for a review, see Young, 2003). Increasing the degree of control that captive animals have over their environments, along with increasing the complexity of the environment, has additional behavioral benefits (Carlstead and Shepherdson, 1994). In this regard, humans are not dissimilar from the rest of the animal kingdom. Although as a species, we are capable of surviving in a broad range of environments, our psychological well-being and normal brain functioning depend on interacting with rich meaningful sensory environments (Schooler, 1984).

As studies of environmental enrichment in zoo settings have pointed out, targeting the dominant sense of the species in question is likely to result in the greatest benefits in terms of well-being. Because humans are predominantly visual animals, providing visual stimulation is particularly important. However, it is also important to provide sensory stimulation in other areas – including audition, sensation, taste, smell, and proprioception. In fact, the greatest benefits will likely come from integrated sensory stimulation.

Visual stimulation. Visual stimulation in the capsule environment can be increased through the use of varied colors, shapes and textures (Stuster, 1996) and, as described in the previous section, these elements are particularly meaningful if used to assist orientation and space differentiation. There has been some research on the relationship between color and mood, for example a specific shade of pink has been found to relieve stress on submarines and in prison cells (Gallagher, 1993), although there is not much hard evidence for a "right" color for particular people or environments.

Including plants and other nature elements in the capsule environment is a particularly effective way to introduce visual stimulation. People have an innate affinity for nature (Wilson, 1984; Kaplan and Kaplan, 1989) and plants provide varied stimulation as they grow and change. Plants also stimulate multiple senses (visual, olfactory, tactile, and possibly gustatory) and can aid in mental restoration (as discussed in more detail below).

Auditory stimulation. Music has long been used in ICE environments to provide auditory stimulation and help relieve the tedium of routine or low engagement work. The benefits of music are well documented and include improvements in mood (e.g., Sousou, 1997; McCraty et al., 1998), behavior (e.g., Ragneskog et al., 1996; Yalch and Spangenberg, 2000), and social functioning (Brotons et al., 1997). A number of studies show specific benefits for classical music (for a review, see Wells, 2009).

Bluth and Helppie (1986) provide specific recommendations for music styles in spaceflight environments, although music choice is probably best left to the crew. Auditory stimulation can also come from other background sounds, such as the sounds of rain, birds, or wind. Although music and other sounds can provide rich and meaningful auditory stimulation while helping focus the mind and providing cognitive clarity, they can also be a source of distraction, particularly during tasks that take a great deal of thought or concentration. Thus, background music and sounds, pleasant though they may be, must be completely under the control of crew members.

Stimulating the other senses. Olfactory stimulation has been used to treat a range of human ailments (i.e., aromatherapy) and there is some evidence that essential oils and other aromatic plant compounds can be used to reduce anxiety and improve mood (e.g., lavender, chamomile; Schwartz et al., 1986; Roberts and Williams, 1992; Moss et al., 2003) and increase alertness (e.g., peppermint, rosemary; Kovar et al., 1987; Diego et al., 1998; Warm and Dember, 1991). In addition, synthetic pheromones have been used in animal populations to reduce stress (Falewee et al., 2006; Driessen et al., 2008) and decrease aggression (McGlone et al., 1987; Petherick and Blackshaw, 1987). Natural or synthetic aromas could be used in the capsule environment, although careful consideration would need to be given to sensitivities of individual crew members.

Another avenue of increasing meaningful stimuli is through maximally varied food choices. Many crew members (even on relatively short duration missions) complain of menu monotony (Stuster, 2010). A wide range of food not only increases sensory stimulation but also boosts morale. In addition, unexpected treats in some food containers provide novelty and boost mood. Stuster (2010) also suggests including food items that can be assembled by crew members into a special treat, for example for special shared meals.

Environmental enrichment in the capsule context

Attention to environmental enrichment should permeate capsule design but it bears repeating that enrichment should be done in a way that is relevant and meaningful to the capsule inhabitants. Stimuli that do not support one's purpose (e.g., background music when one is trying to focus, a jumble of colors that inhibit rather than support wayfinding, a visual cacophony of cords, tubes, and stowage) are distractions and are a psychological negative.

Even stimuli that are inherently interesting can prove more of a distraction than a positive. This is particularly true in the case of stimuli that fall into the category of "hard fascination" – those that draw and tend to rivet one's attention. Television certainly falls into this category as does music with a strong and compelling beat or lyrics. Although stimuli with hard fascination may have their place in the capsule environment, they should be used judiciously, be under the control of crew members, and be situated in a way that does not detract from other activities (e.g., work, sleep). Elements that capture attention in a less riveting manner (those with "soft fascination"), on the other hand, tend to fit with multiple purposes and can provide a rich array of meaningful and compatible stimuli. Examples include plants and other nature elements, images of water, soft background nature sounds such as from a trickling stream, and some music.

A final consideration is sensory variability. No matter how lovely, the same nature image or Mozart sonata will lose some of its impact and appeal if it is seen or heard day after day.

Reduce distractions

Two of the most pervasive distractions in capsules are background noise and visual clutter. Constant levels of background noise, such as that from fans and equipment, increase stress and reduce one's ability to concentrate. People do not habituate to this noise; instead, negative effects tend to increase over time (Jahncke et al., 2011). Noise can be dampened somewhat with appropriate insulation and the use of sound-absorbing tiles. More active noise cancellation technology, such as noise cancellation speakers or headphones can also be effective, particularly with low frequency noise (Cunefare, 2004; Milosevic et al., 1998).

Reducing visual clutter is largely a matter of design. Cargo stowage systems could be designed so that cargo is visually contained, for example in color-coded easily adaptable bins or cubicles; such a system could also facilitate cargo organization. Tubes and wires, particularly those not requiring daily access, could be contained and hidden behind lightweight panels or by other means.

Adequate Lighting

Proper lighting and light variability is essential for visual stimulation, work efficiency and safety, and proper sleep. Lighting requirements depend on activity. For example, detailed work and inspection generally requires 1500 lux or more, while the appropriate level for computer work is much lower (in the vicinity of 300-500 lux) in order to minimize glare and maximize the contrast between screen and background. Light levels in the vicinity of 200 - 500 lux are generally acceptable in areas that require less concentration and visual acuity, such as dining rooms, bedrooms, and common areas (Chartered Institute of Building Services Engineers, 2003). Because of the variability in lighting needs, lighting should be fully adjustable and should include both general and task lighting. A sufficient number of portable lamps and sockets

throughout the capsule will help ensure that crew members have lighting when and where they need it. In addition, proper consideration should be given to reflection from walls and equipment as glare and excess light can reduce productivity and have negative effects such as headaches (DiLouie, 2006; Bluth and Helppie, 1986).

Light is important not only in terms of work but also in terms of general health and well-being and proper lighting is an important countermeasure for the disruption of sleep and circadian rhythms observed during spaceflight (Fucci et al., 2005). In particular, regular exposure to natural sunlight is associated with increased worker satisfaction and mood (Edwards and Torcellini, 2002) and plays a critical role in maintaining circadian rhythm and regulating other biological functions (Mead, 2008). When these functions are disrupted, problems can include seasonal affective disorder (SAD), delayed sleep phase syndrome, and other psychiatric and health disorders (Boivin, 2000; Weitzman et al., 1981; Figueiro et al., 2006; Figueiro and Rea, 2010; Rea et al., 2008).

Although there is conflicting evidence regarding whether or not full spectrum artificial light has psychological benefits at lower levels of illumination (and thus whether it would be beneficial to use full spectrum light in living and work areas), there is solid evidence that light therapy can help mitigate some of the risks from lack of regular exposure to sunlight. Bright light therapy (exposure to full spectrum light of up to 10,000 lux for 30-60 minutes at a specific time or times of day) has been shown to effectively treat symptoms of SAD and delayed sleep phase syndrome (Paino et al., 2009; Lam et al., 2006; Rosenthal et al., 1990) and may be useful in prevention as well as treatment.

Appropriate Workload

In his analysis of over 4,200 journal entries by astronauts in the International Space Station, Stuster (2010) found that the most frequently mentioned thing was the pressure of work schedules. Stress occurs both as a result of relentless scheduling (e.g., in the ISS, almost every minute of an astronaut's time is scheduled) and insufficient time allotted to complete tasks. Having insufficient time to complete tasks is particularly damaging: not only does it compromise the quality of the work and induce stress during the task, but it can undermine one's sense of competence, thereby contributing to a more chronic stress. Sufficient time must be scheduled for all tasks, including time buffers for when something goes wrong. Crew should have input into the scheduling of tasks and some time should be left unscheduled by ground control (i.e., should be under direct control of crew members).

"MODIFYING" CREW TO IMPROVE FIT

Because there are many basic informational and social needs that all humans share, psychological risk factors in spaceflight and other ICE environments cannot be human-engineered out of the equation. However, people do vary: some may have a greater need for understanding while others might have a greater need for exploration. Some may rely on the external environment for much of their mental stimulation, while others may be more internally stimulated. Some will have greater directed attention capacity than others. Because of this individual variability, we would expect some individuals to fare better than others in long-duration spaceflight environments. In addition, coping skills can be increased through proper

training. The goal, then, of crew selection and training, from the perspective of psychological well-being, is to improve crew response to stressors in the spaceflight environment.

Implications for Crew Selection

Selecting individuals for a space mission involved a series of tests and profiling to identify any medical, psychological, or social problems and to assess personality, performance, stress tolerance, and group compatibility (Santy, 1994). Although it is beyond the scope of this study to discuss these selection factors in details, it is important to note that the demands of longer-duration and longer distance missions, where one will be exposed to environmental stressors for a much greater period of time and communication with Earth will be greatly reduced, may have different implications in terms of selection. In addition to other personality factors, we would expect the following characteristics to be associated with better outcomes in long-duration spaceflight environments:

Less reliant on external support. Some people are highly dependent on social interaction for support and stimulation, while others draw more strength from within (Biderman and Zimmer, 1961). People toward the latter end of this scale are likely to cope better with social isolation.

Self aware. The negative consequences of long term environmental stress and coping are not always easy to detect in oneself. Additionally, actively employing countermeasures for mental fatigue and seeking help for psychological issues is not easy in a culture that selects for and encourages tough-mindedness, a can-do attitude, and distain for weakness. However, recognizing and ameliorating the signs and symptoms of stress will be critical for mission success and individuals must have strong self-awareness, an ability to recognize and admit to potential personal and interpersonal problems, and a willingness to deal with these issues.

Rich intellectual environment. Those who rely more on their own intellectual activity and imagination than on the external environment for stimulation are more likely to succeed in the stimulus poor environment of long-duration spaceflight. Suedfeld (1991) uses the term "deepeners" to describe those people who are able to remain intellectually engaged in a superficially monotonous setting. Similarly, Admiral Richard Byrd, an early American Antarctic explorer, describes successful Antarctic explorers as those who are able to look, "… inside themselves for materials of replenishment ... For there is no escape anywhere. You are hemmed in on every side by your own inadequacies and the crowding measures of your associates. The ones who survive with a measure of happiness are those who can live profoundly off their intellectual resources as hibernating animals live off their fat" (as quoted in McKee, 2000).

Creative decision makers able to both follow directions and to act autonomously. In today's highly prescribed space missions, the ideal candidate may be an exceptionally capable adult who takes direction and follows rules like an exceptionally well-behaved child (Roach, 2010). In a mission to Mars, however, crew members will likely experience a 20-minute radio transmission lag time, periods without communication, and unexpected situations. Functioning well in this environment will require a degree of creativity and an ability to make one's own decisions, sometimes under pressure or uncertainty. Similarly, in long-duration isolated-duty assignments in Antarctica, those who fare best have been found to be mature, realistic, and independent (Smith, 1966; Taylor and Shurley, 1971).

Socially compatible with rest of crew. Much has been written about the importance of social compatibility and group cohesion among spaceflight crews (Vakoch, 2011; Simon et al., 2011) and selecting for positive group dynamics is critical. Groups who get along, work well together, and can provide some social support for one another will experience less stress from the social environment and will be more able to cope with other environmental stressors. To some extent, one can select individuals with personality and demographic (e.g., age, gender, skill set) profiles that will make it more likely they will get along with others (Suedfeld and Steel, 2000). However, group functioning cannot be completely predicted or controlled through individual selection. This fact argues for allowing crew members at least some input in the selection process. It also highlights the importance of assessing group dynamics in simulated environments as part of the selection process. (Role plays, groups discussions, and group exercises, for example, have been found to predict job performance in other contexts (Hunter and Hunter, 1984)).

Implications for Pre-Flight Training

Because environmental stress is often reduced with predictability, familiarity, and understanding, preflight training is an important avenue for increasing human environment fit. Part of training should be focused on educating candidates about the problems that may arise, as people are generally better able to cope when they know that some conflict and problems are inevitable (Levine, 1991). Training in communication, intercultural understanding and conflict resolution can help to mitigate some of the conflict that is almost inevitable when a small group of people must interact closely over a prolonged period of time. In addition, astronauts should be trained to recognize the signs of mental fatigue and sleep deprivation and to implement coping strategies. As former NASA space psychologist, Patricia Santy, writes, "People who make good astronauts are not particularly insightful individuals in general. They have what can be called an 'anti-psychological attitude' and believe they can cope with anything on their own" (Oberg, 2007).

Training should also include simulated experiences, preferably of gradually increasing length. Not only do these simulations provide valuable information about individual personality and group dynamics, but they also increase candidates' understanding of the environment and expected environmental stressors and provide them with opportunities to develop coping skills. Participants in repeated isolation experiments, for example, report that each experience was easier than the last; repeated experience was also associated with improvements in cognitive test scores (Zubek, 1973; Ruff et al., 1961). As Poynter (2006, p.300) wrote, after her stay in Biosphere 2, "For some reason, it seems impossible to convey the severity of the psychological and social challenges in isolated and confined environments – they have to be experienced to be believed, especially by Type A, self-assured individuals."

COUNTERMEASURES FOR INHERENT ENVIRONMENTAL STRESSORS

Selecting the right individuals, providing them with appropriate training, and designing the environment to minimize stressors are important aspects of improving human-environment fit and reducing the risk of psychological and behavioral problems in the context of long-duration spaceflight. They are, however, not enough. The nature of the space environment, and ICE environments in general, is such that physical and human engineering alone are unlikely to reduce environmental stress to acceptable levels. Given this reality, it is essential to develop and provide additional countermeasures to assist people in coping with and recovering from the mental costs associated with environmental stressors that cannot be eliminated.

The goal of countermeasures to environmental stressors in the spaceflight environment, from the perspective of psychological well-being, is to (1) provide intellectual stimulation, (2) assist in the recovery of directed attention and the reduction of overall stress, (3) provide social support, and (4) foster group cohesion and positive group dynamics.

Each of these categories of countermeasures is discussed separately below, although specific strategies and activities may address multiple categories.

Increasing Intellectual Stimulation

Although environmental enrichment is typically restricted to a discussion of the external (sensory) environment, it is also important to consider countermeasures focused on enriching the internal (intellectual) environment.

Dozens of studies show a link between education and the risk of dementia (for a review, see Jankowsky et al., 2005) and support the hypothesis that increased mental activity leads to stronger, more highly elaborated neural structures that are more resistant to disease. Indeed, activities such as reading, crosswords and other puzzles, cognitive challenging games such as chess, self-directed education, hobbies, and socializing have been shown to help maintain cognitive functioning (Lusting et al., 2009; Eskes et al., 2010; Daffner, 2010). Even among those suffering from dementia, cognitive stimulation therapy (e.g., games, multi-sensory stimulation, activities focused on information processing) offers some benefits in terms of cognitive functioning and reduced depression and anxiety (Spector et al., 2003). Likewise, cognitive therapy, including the use of virtual reality environments, that focuses on executive functions such as memory, planning, and spatial knowledge representation, is widely and effectively used in the rehabilitation of cognitive functioning following stroke or other cognitive impairment (Morganti, 2004).

Given the importance of intellectual stimulation in maintaining neurophysiological and psychological health, along with the importance discussed in the previous chapter on having opportunities to use and extend knowledge, countermeasures that provide intellectual stimulation are critical in the spaceflight environment. The most important of these is ensuring that crew members have a sufficient amount of engaging work.

Meaningful work: engagement and control. Stuster (2010) found that the single most important factor in an astronaut's adjustment to life in space was having meaningful work. Spaceflight crew members are generally highly motivated and high achieving individuals who can react negatively to tedious, repetitive highly prescribed work (Simon et al., 2011; Stuster, 2010). Although nearly every job requires one to do at least some work that is not particularly stimulating, there must be a balance between routine work and work that is engaging and provides a challenge, between work and scheduling that are pre-determined and those that are self-defined. The goal, as Lebedev (1988, p. 259) puts it, is to feel like an "intelligent man [one might say person] in control." Having a sufficient amount of engaging work that is, at least to some extent, self-determined in content and scheduling will be particularly important on long-duration missions where there will be more time to become bored.

Intellectual stimulation during leisure time. Although historically astronauts have not had a great deal of leisure time, long-duration missions (e.g., a mission to Mars) will be marked by long periods of time where there is not much to do. In the absence of engaging prescribed work, other avenues of intellectual stimulation will become increasingly important. In a review of accounts of six long-duration space mission, Peldszus (2011) found that two of the most important activities for maintaining well-being were pursing personal science projects and creatively using onboard materials (e.g., printer, cameras, and other supplies) to produce functional or entertaining objects.

Countermeasures that focus on cognitive stimulation must be enjoyable and thus will differ from individual to individual, but may include reading, writing, puzzles and games, computer simulations, hobbies and other personal projects. Given people's inherent need to have a sense of purpose and engage in meaningful activities (Kaplan and Kaplan, 2009), intellectual activities that have a broader purpose (e.g., a personal on-going project) will be particularly effective countermeasures. Play and creative expression are also important forms of intellectual stimulation, whether in the form of music or other artistic endeavors (Schlacht and Ono, 2009) or in the form of improvising a game out of duct tape and chocolate balls (Häuplick-Meusburger et al., 2010).

Physical Exercise

Physical exercise is not only a critical countermeasure for the negative effects of microgravity on muscle mass and bone density (Carpenter et al., 2010) it is also a significant factor in maintaining brain health and mitigating some of the neurophysiologic changes brought about by low stimulus environments. A number of studies indicate that physical activity is associated with lower risk for developing cognitive impairment and dementia and with better performance on tests of general cognition and attention (Daffner, 2010; Yaffee et al., 2009; Weuve et al., 2004; Larson et al., 2006). Furthermore, animal studies indicate that exercise supports neuron survival and promotes synaptic connections (Hillman et al., 2008; Churchill et al., 2002; Neeper et al., 1996).

Despite the critical nature of exercise, many space crew members express negative feelings toward it (Bluth and Helppie, 1986), likely because, as currently practiced, it can be boring, monotonous, heavy work. Finding ways to make exercise more enjoyable will have positive benefits in terms of both physical and mental outcomes. Consideration should also be given to

combining exercise with some of the other countermeasures outlined below. For example, providing a nature immersion experience while exercising could simulate the experience of biking or running through an enjoyable natural setting and would motivate one to exercise while providing an opportunity for mental restoration. Likewise, other exercise-based simulations (for example those found on the Nintendo Wii or Microsoft XBox Kinect systems) would also be motivating and could be done socially.

Restoring Attention and Reducing Stress

As mentioned earlier, sleep is one of most effective ways of restoring attention capacity, and implementing countermeasures for sleep loss (such as reducing noise and other environmental distractions, designing maximally comfortable sleeping systems, scheduling time for daytime naps, and pharmacological approaches) is important. But as we've seen, in cases of severe fatigue or continued functioning in stressful environments, sleep is not enough. Indeed, the insomnia and disrupted sleep patterns that commonly develop in ICE environments would make recovery from DAF through sleep alone almost impossible. What are the best environments and activities for mental restoration? Attention Restoration Theory (ART, Kaplan and Kaplan, 1989; Kaplan, 1995; Berman and Kaplan, 2010) developed from an analysis of the types of settings that promote recovery of directed attention. Based on ART, there are four main components of restorative environments and experiences:

Fascination. As described in the previous chapter, when involuntary attention is engaged by inherently fascinating stimuli, directed attention can rest and restore. Fascination can be process-based (e.g., mystery stories, gambling) or content-based (e.g., animals, nature). It can be "hard," dominating our thoughts and making it difficult to think of anything else, or "soft," calling on involuntary attention in a pleasant and quieter way that leaves room for other thoughts. Soft fascination (e.g. the type of attention engaged by nature sights and sounds) has advantages in mental restoration in that it provides an opportunity for reflection and for processing troubling thoughts, thereby reducing internal distraction and lessening the need for directed attention to keep those thoughts at bay in the future. Although fascination is a central concept in ART, it is but one important component of a restorative setting.

Being away. Restoring attention requires getting away from the current attention depleting environment or activity. In this sense, "being away" is conceptual rather than strictly physical. The sense of being away could be achieved by placing oneself in a whole new space, but it could also be achieved through something as simple as changing one's gaze or bringing one's focus inward through, for example, meditation.

Extent. To be restorative, environments and experiences must be of sufficient scope and coherence to engage the mind. A jumble of fascinating stimuli does not have extent because it lack coherence while a large environment with little going on lacks extent despite its size because there is not enough to engage the mind. Extensive environments are not necessarily physically extensive. Although they can be large (e.g., a park or wilderness setting), they can also be quite small (e.g., a bonsai tree or miniature garden); they can even be conceptual rather than physical (e.g., a play, compelling novel, or virtual natural environment).

Compatibility. Finally, for an environment to be restorative, there must be compatibility between the setting and what one is trying to do. The individual should be able to function smoothly and without struggle (Kaplan, 1983). An environment that leaves one confused, that requires knowledge or skills that one does not have, will not be restorative.

The special role of nature in mental restoration and stress reduction

Although a wide range of activities (e.g., reading, journal writing, music, long baths, watching a play, quiet socializing) provide at least some opportunity for attention restoration, one of the most effective is exposure to nature and natural elements (Kaplan, 1995). Natural settings tend to be high in all four requirements for restoration. They are full of soft fascination (both in terms of process – like the rustling of the wind and changing light – and in terms of content – like plants, birds, and water). In addition, nature can provide a sense of being away from it all and it is typically high in extent. Finally, the special resonance that humans have with nature makes natural environments highly compatible.

There is a rich body of research on the positive effects of nature and natural settings on attention capacity, stress, mood, behavior, vitality, and physical health (for reviews, see Kaplan and Kaplan, 1989; Bird, 2007; Frumkin, 2001; Pretty et al., 2005; Kuo, 2004). Positive effects have been found for both active and passive interaction with nature (walking or sitting in nature, gardening, viewing nature from the window) and for a wide range of types and scales of nature, from wilderness settings to a plant on one's desk. The beneficial effects of nature appear to be due to both a recovery of direction attention and a reduction in physiological stress, with attention recovery generally requiring longer exposure to nature than psychophysioloical stress recovery (Kort et al., 2006; Hartig et al., 2003).

Being in nature. Being in nature (walking, sitting, gardening) is a particularly powerful way to restore directed attention capacity and lower physiological stress. In a recent study, Berman et al. (2008) compared the effects of walking in a nature or an urban setting on mood and attention capacity. Prior to the walks, study participants' mood and attention capacity were assessed and then they completed a short term memory task designed to induce mental fatigue. Participants were then randomly assigned to a 2.8 mile walk (50-55 min) in either a nature or downtown setting. Study results showed that following the walk, attention capacity had increased significantly for the nature walkers but not for the urban walkers. Mood improved for both groups, but more so for the nature group. A number of other studies have similarly shown increases in attention capacity, mood, energy, and psychological functioning following walking or sitting in nature (Hartig et al., 1991; Kaplan and Talbot, 1983; Ryan et al., 2010; Mayer et al., 2009; Cimprich, 1993) as well as a reduction in symptoms of psychological disorders, such as ADD (Kuo and Taylor Faber, 2004; Faber Taylor and Kuo, 2009).

In addition to the benefits of nature in terms of attention capacity and mental functioning, time spend in nature has also been shown to have a direct effect on physiological stress. Tsunetsugu et al. (2007), for example, have shown that 15-20 minutes of exposure to natural environments, as compared to urban environments, lowered blood pressure, pulse rate, and cortisol levels. Others have found similar results (Hartig et al., 2003; Van den Berg, 2006).

Although the majority of studies on the psychological and physiological effects of nature explore the effects of a one-time exposure, there is evidence that repeated nature exposure over a longer

period of time can help with attention recovery in cases of more severe DAF and can help buffer one from on-going stress. Cimprich's (1993) study of post-operative breast cancer patients found that although this population showed particularly high and chronic levels of DAF, study participants who engaged in restorative nature activities (i.e., walking in nature or gardening) 20 minutes a day three times a week over a period of three months, showed dramatic improvement in their psychological health, including their attention capacity. Similarly, Canin (1991) found that the single most powerful factor in avoiding burn-out among AIDS caregivers was regular locomotion in nature (walking, running, or biking).

Plants and gardening. The benefits of interacting with plants are so well accepted that horticultural therapy and healing gardens are commonly used in hospitals and other care facilities, particularly with the elderly, the highly stressed and those with special needs (Ulrich, 2002; Cooper-Marcus and Barnes, 1999). Gardening and other interactions with plants combine the restorative benefits of nature with additional benefits that come from sensory stimulation, being outside, and caring for living things (Rossman and Ulehla, 1977; Hartig et al., 1991; Hartig et al., 2003; Herzog et al., 2002).

But interactions with plants need not be active to be beneficial. Research shows that something as simple as having a plant on one's desk provides a micro-restorative opportunity and also increases positive feelings towards work (Laviana et al., 1983). Plants in the workplace and in hospital settings are associated with reduced sick leave, increased productivity, increased attention capacity, reduced stress, and increased pain tolerance (Raanaas et al., 2011; Lohr, et al., 1996; Shibata and Suzuki, 2001 and 2004; Bringslimark et al., 2007; Fjeld, 2000). Office workers seem to intuitively sense the benefits of plants: one study of 385 Norwegian office workers found that workers without windows (and thus without nature views out the window) were much more likely to bring in plants for their work areas than were workers with windows (independent of age, gender, type of office, job demands, and level of personalization of work space) (Bringslimark et al., 2011).

Although plants in spaceflight environments have largely been studied from engineering and biology perspectives, interaction with plants and plant growth facilities have been reported by flight crew member as restorative (Peldszus, 2011). The inclusion of plants and small gardens in space capsules could provide crew with micro-restorative opportunities, having positive effects on mental functioning, mood, and stress levels. As mentioned in the previous section, plants would also provide some welcome sensory stimulation. Cosmonaut Lebedev (1988) captured the value of having plants in the space capsule environment when he wrote that during his 211 days in flight he loved the little space garden because, "When I smell it, it seems I can smell the Earth. I feel great" (p. 86). When the plants were later sent back to Earth with a visiting crew, he wrote, "… we feel sad and uncomfortable without our garden and without our dear plants. It was such a pleasure to take care of them" (p. 255).

Nature views. One does not necessarily have to be physically in a natural setting in order to realize the psychological and physiological benefits of nature. Simply having a view of nature out one's window can be enough. Ulrich's (1984) study of hospital patients recovering from gall bladder surgery found that patients with a view of trees out their window had significantly shorter post-operative stays, fewer minor post-operative complaints, and less use of painkillers

than did patients with a view of a brick wall out their window. Similar results have been found in prison settings (Moore, 1981).

Some of the benefits of nature views appear to be mediated through a reduction in physiological stress. Other research shows that benefits are also mediated through a recovery of directed attention capacity. In a series of studies in the Robert Taylor Homes Public Housing Project in Chicago, Kuo, Sullivan, and their colleagues have shown that having a view of nature from one's residence (as opposed to a view of concrete) is associated with higher levels of directed attention capacity and that this, in turn, has a range of benefits including significantly lower levels of aggression and violence, less impulsivity, increased ability to delay gratification, and better concentration and self-discipline (Taylor et al., 2002; Kuo and Sullivan, 2001; Kuo, 2001; Coley et al., 1997). A number of other studies show that even among less inherently stressed populations there are significant benefits of window views of nature in terms of attention restoration, stress reduction, and general well-being (Hartig et al., 2003; Tennessen and Cimprich, 1995; Kaplan, 1993; Kaplan, 2001; Leather et al., 1998; Shin, 2007).

Although there is limited data on the psychological benefits of windows in space capsule settings, porthole views of Earth are clearly fascinating for crew members and it is highly likely that they provide significant benefits in terms of attention recovery and stress reduction. In his study of coping strategies that astronauts employ to mitigate the inherent stress of long-duration confinement in the ISS, Robinson and his colleagues (Robinson et al., 2011) found that the most commonly reported enriching activities had to do with perceptions of Earth (both viewing and photographing). Others have similarly found that spaceflight crew members spend much of their off-duty time looking out the window at views of Earth and gain significant psychological benefits from doing so (Gurovskiy et al., 1980; Johnson, 1974; Haines, 1991; Miller and Kublick, 1984; Radloff and Helmreich, 1968). As one ISS astronaut put it, "It’s become a ritual for me, on my way home from the Service Module at night, to take a detour and stop in the Russian Docking Compartment to stare out the window before I go to bed. The view is awe inspiring and beyond comprehension" (Stuster, 2010, p. 24).

Substitutes for nature views and experiences

As important as views from the window are in space missions near Earth, in longer distance exploration missions, such as a mission to Mars, there will be little to see out the portholes for long periods of time. These long-duration missions will require substitutes for nature settings and views (Robinson et al., 2011). But does simulated nature have the same positive psychological and physiological benefits as real nature?

Nature images and videos. Studies on the restorative and stress reduction benefits of nature support the notion that static images of nature can have effects similar to walking in nature. For example, Berman et al. (2008) ran a follow-up study to their comparison of the effectiveness of nature and urban walks in restoring attention capacity. This second study was similar to the first except that participants viewed pictures (projected slides) of either a natural or urban environment for 10 minutes in a quiet room. The results were similar to the first study: directed attention capacity was significantly improved following the exposure to nature images but not to the urban images (although the improvement was somewhat less than that seen for walking in nature). A number of other studies similarly show that simply viewing images of nature can

have significant psychological and physiological benefits (Berto, 2005; Ulrich et al., 1993; Heerwagen and Orians, 1993; Orians and Heerwagen, 1992).

Nature experiences via video can also have significant positive effects from the perspective of psychological well-being (Lauman et al., 2003, Kahn et al., 2008; Mayer et al., 2009; Depledge et al., 2011), although the effects are generally not as great as actually being in a natural setting. Ulrich et al. (1991), for example, found that stress recovery was significantly more rapid after exposure to a video of natural settings versus urban settings. Similarly, researchers have found that watching videos of driving through natural settings reduced stress levels and provided some immunization from subsequent stress (Parsons et al., 1998; Cackowski and Nasar, 2003). Mayer et al. (2009) studied the impacts of nature exposure on the ability to reflect and solve problems. They asked study participants to consider a relatively minor problem in life while strolling through a natural or urban setting or while watching a video of those settings. Results showed that exposure to both actual and video nature increased one's ability to resolve personal problems, although actual nature was more effective than the video nature.

Although the benefits of nature surrogates have not been rigorously studied in the context of ICE environments, there is some anecdotal evidence that videos of natural scenery are especially appealing to space crew (Gurovskiy et al., 1980 as cited in Clearwater and Coss, 1991) and that images of nature may have a relaxing effect (Clearwater and Coss, 1991).

Simulated window views. The architect Christopher Alexander wrote, "Rooms without a view are prisons for the people who have to stay in them" (Alexander et al., 1977, p. 80). But in environments where windows are not possible or where there is nothing to see outside the window, can simulated window views provide an effective substitute? Research on the benefits of simulated window views of nature is scant and the results are mixed. A study by Friedman et al. (2004) suggests that virtual windows can have wide-ranging positive impacts. They installed virtual windows (50" plasma screens displaying a real time local nature view) in the windowless offices of university faculty and staff over a 16 week period. At the end of the study period, participants reported an increase in psychological well-being, cognitive functioning, connection to the wider social community, and connection to the natural world.

A later study (Kahn et al., 2008), showed that a virtual window (in this case, a plasma screen hung over the real window) was not as effective as a real window at restoring heart rate after cognitive stress. Results also showed that participants spent significantly more time looking out the window than at the screen. More specifically, the plasma screen drew participants' attention at the same rate as the window, but did not hold their attention as long. Although the study has a number of significant limitations – no measures were made of attentional or other psychological functioning and the screen clearly looked like a television screen and not a window – it does highlight the importance of engagement (i.e., time spent and level of immersion in the environment) in achieving maximal psychological and physical benefits.

Virtual reality and simulated environments. Engagement with and immersion in a simulated environment is the goal of virtual reality (VR) technology. VR systems strive to create sensory illusions sufficient enough to produce a plausible and immersive simulation of a particular environment. Studies on the use of VR in neuroscience and psychological research indicate that cognitive, emotional, and behavioral responses to quality VREs (virtual reality environments) are analogous to those to the real world (Bohil et al., 2011; Loomis et al., 1999). For example, placing

an acrophobic in a VRE that mimics being in a high place elicits the same physical stress response as actually being in a high place.

There are a number of ways of creating immersive virtual environments. One of the most common in VR research and training is using a head mounted display in conjunction with a computer and a head tracker (and possibly with trackers on other parts of the body, for example, embedded in gloves which can also provide kinesthetic stimulation and feedback). Other VR systems (e.g., CAVE) use multiple projection screens, viewed through glasses so that one sees the projections not as two dimensional images on the room surfaces, but as a solid three dimensional structures (Loomis et al., 1999; Crug-Neira et al., 1993).

Despite the promise of VREs, they are not without their problems. Most notably, they are cumbersome to wear and store (relying on complex hardware and software and requiring the user to wear head trackers, goggles, and other devices), unreliable (providing a limited field of view, slow graphics and update rate, and lags between head tracking and visual display) and expensive (Loomis et al., 1999). In addition, "cybersickness" (nausea after using a VRE system) is not uncommon (Bohil et al., 2011). This nausea is hypothesized to stem from an incongruity between sensory inputs from the virtual and physical worlds (e.g., difference in actual and simulated motion or assumed and actual gravitational force) and may be particularly problematic in spaceflight environments.

More recently, advances in personal computers and gaming technology have produced a variety of VRE systems that do not strive for the same degree of sensory isolation from the real world as traditional VR systems but that do have significant advantages in terms of simplicity and cost. Nintendo's Wii and Microsoft's XBox Kinect, for example, deliver strong visual and auditory simulations of environments and employ user-friendly technology to track motion and integrate it with the simulated environment. In addition, a host of design systems now make it relatively easy to create virtual environments on home computers.

There is little data specifically on the effectiveness of VREs as nature substitutes, but preliminary studies on the psychophysiological effects of virtual natural environments show they can have effects similar to interaction with real nature. The Virtual Restorative Environment Therapy (VRET) Initiative, for example, studies the psychophysiological effects of virtual nature simulations run on a desktop computer and assesses the impact of various environmental characteristics, such as weather, wave strength, ambient sounds and smells (Depledge et al., 2011).

Although VR systems and other computer simulations offer a great deal of control over the simulated environment, there is no data supporting the notion that they are better – in terms of restoring attention capacity, improving mood, reducing stress, and otherwise providing a countermeasure for environmental risk factors – than simulations of natural environments that rely on much simpler technology, for example the use of slides and video of actual (as opposed to computer generated) environments along with other sensory stimuli such as nature sounds and smells. Research on simulated environments indicates that what matters in terms of eliciting the desired response is not so much the specific technology employed, but the degree of *immersion*, or level of engagement, in the simulated environment and the degree of *presence*, or the sensation of actually being in the environment (Bohil et al., 2011; de Kort and Ijsselsteijn, 2006). These concepts are similar to two of the components of restorative environments discussed earlier – namely, *extent* and *being away*. And of course, overlaying these concepts is the

importance of content – content is critical to both creating a sense of immersion (Stone, 2008), and to eliciting the desired psychological or physiological response (i.e., picking nature content high in soft fascination to create a setting that promotes mental restoration and stress reduction).

One example of a low tech yet effective environmental simulation is the "psychological relief room" used in a study of factory workers in the former Soviet Union (Clearwater and Coss, 1991; Bluth and Helppie, 1986). The study demonstrated that factory workers who experienced 10 minutes of multi-sensory simulations of wilderness settings (large scale projections of nature, music, and nature sounds) after they had been working for long enough to experience mental fatigue showed significant post-session improvement in state of mind, work capacity, attention, and reaction speed.

Implementing nature-based countermeasures in the capsule environment

Based on this review of countermeasures research, several nature-based strategies emerge as particularly promising in the capsule environment and certainly worthy of research. An additional strength of these strategies is that while they provide an opportunity to recover from the stress and mental fatigue of long-duration spaceflight, they simultaneously address one or more other risk factors (e.g., by providing sensory stimulation, increasing motivation for physical exercise, or providing a sense of connection with Earth).

Immersive nature experiences. Simulated immersive nature experiences have the potential to provide an opportunity for deep mental restoration and stress reduction. As discussed, for maximal effectiveness in eliciting a psychological, neurological, or behavioral response, simulated environments must foster sense of immersion, or extent, and of presence, or being away from the capsule environment and "being in" the simulated environment. In addition, content is a critical component of restorative environments. A simulated experience of the Indi 500 – or, for that matter, a dramatic scene of a pack of lions bringing down a gazelle – may succeed in fostering a sense of immersion and presence but will leave little mental space for reflection and relaxation and will thus not be nearly as effective in restoring attention capacity and reducing overall stress as would a nature scene full of soft fascination. Important characteristics to consider, then, when creating simulated immersive nature experiences for the capsule environment are *content*, *degree of stimuli richness*, and *creating a sense of presence*.

Content. Studies of restorative environments suggest that natural settings full of soft fascination are particularly restorative. Components of soft fascination include vegetation (particularly trees), gardens, landscaped areas, vistas, non-threatening animals, familiar and pleasant natural odors, and nature sounds such as birds, running water, and rustling leaves. Water is a particularly powerful restorative element (Bird, 2007; Kaplan and Kaplan, 1989). In addition, some built elements are at home in restorative environments, if they are compatible with the natural settings; examples include trails and pathways made from dirt or natural materials, wooden bridges, and Japanese garden fixtures (Kaplan et al., 1998).

The vast literature on environmental preference offers a good foundation for identifying the characteristics of restorative environments as there is a connection between how restorative people find an environment and how much they like it (Hartig and Evans, 1993; for a review of preference research, see Kaplan and Kaplan, 1989). In addition to nature content, the pattern of environmental stimuli is important. Kaplan and Kaplan have analyzed many studies on

environmental preference and identified the strong role that environmental pattern plays in preference, particularly, the following four characteristics: (1) *complexity*, or the richness of the environment, (2) *coherence*, or the degree to which the environment makes sense or is understandable, (3) *legibility*, or the sense that one could find one's way around the environment without getting lost, and (4) *mystery*, or the sense that something more can be learned as one moves through the environment.

Stimuli richness. Visual stimulation is only part of the story in simulated environments. Other stimuli, such as nature sounds and smells, air temperature and movement, and tactile stimuli are also important in terms of creating an immersive experience (de Kort and Ijsselsteijn, 2006). Research indicates that sound and smells, in particular, can add to the restorative quality of a natural setting (Pheasant et al., 2010; Barnfield and Danas, 1995). In a study comparing the relaxation effects of a natural (30 minutes seated on a bench in a wooded nature park) versus a simulated natural environment (watching a series of slides of the same environment on a 28-inch screen in a quiet dimly lit room), Kjellgren and Buhrkall (2000) found that although both environments significantly reduced stress, the natural environment was better at increasing energy levels and provided a greater sense of being relaxed and away from it all. Participant responses to open ended questions reveal that the difference was likely due to the simulated environment's reduced sensory stimulation. While participants in the real nature treatment noted things such as, "the singing of birds," "a nice smell of flowers," and, "all the sounds and smells and light makes me calm," participants in the simulated nature treatment made comments such as, "something is missing. I cannot experience nature with all of my senses," "too quiet," and, "missing the sounds and smells."

Additional stimuli will not only enhance the restorative capability of the environment, but will also provide additional sensory stimuli to help counteract the negative psychological and physiological effects of an extended stay in the sensory poor and monotonous capsule environment. Adding sound to visual simulations is relatively easy from a technological point of view. Nature sounds are obvious choices, but music (as noted earlier) may also be effective. In addition, recent developments in synthetic scent delivery simplify the integration of scents with other sensory modalities to create multi-sensory simulations (examples include HeadHunter 2000 Inc.'s Scent Palette and Scent Sciences' ScentScape system).

Being there: the importance of image size. To fully experience a restorative environment and maximize its psychological benefits, one must be able to leave (mentally, if not physically) the stressful or attention depleting environment. While a sense of being away can be achieved for short periods of time by something as simple as changing one's gaze, maintaining a sense of being away is possible to the extent that the simulated environment is extensive enough to effectively blot out distractions from the real world. Although content plays a large role in holding attention, so does the size of the simulated environment. In other words, an immersive simulated environment needs to be sufficiently large so that one does not have to use directed attention to blot out the real physical world.

In the case of virtual reality systems, a sense of immersion is created by blocking out the physical environment and presenting the virtual environment through head mounted goggles or visors. In less technology-intensive simulations, for example those using PCs, television, or projected images, immersion is, in part, controlled by the physical size of the image or images.

And studies show that size does matter. Kort et al., (2006), for example studied the effect of 10 minutes of exposure to nature scenes on physiological measures of stress and self-reported affect. They compared the effects of viewing the back-projected images on a 31-inch screen and a 72-inch screen. Results showed that although both treatments had positive effects, there were significantly greater benefits for participants viewing the images on the bigger screen.

In addition to fostering a sense of presence in the environment through factors such as image size, it may be possible to increase engagement by manipulating the viewer's mindset. Duvall (2011), for example asked participants to take three 30 minute nature walks each week for two weeks. One group of participants simply took the walks, while another group was asked to choose one of several prompts for each walk designed to increase awareness and engagement (e.g., "focus on your senses" or "imagine you are an artist looking for beauty in everyday things"). Participants in the engagement treatment showed greater improvements in psychological well-being, including attentional functioning.

Appropriate technology. What does it take to adequately simulate a natural environment? VR technology is continually changing, and certainly has a critical role to play in training and skill maintenance (Briggs, 1996). Current VR technology, however, remains relatively expensive and is hard pressed to compete with the realism of film and slides. Another drawback to VR technology is the limit on the variety of simulated settings that are possible due to the amount of time required to develop a single setting. This is not to imply that VR technology has no role in developing countermeasures for long-duration spaceflight – indeed, the day of a truly immersive holodeck may not be too far off. On the other hand, the allure of technology should not take attention away from other, less technology intensive, methods of simulating environments that may be just as – or more – effective in terms of their psychological and physiological benefits.

A relatively simple (from a technological perspective) yet potentially highly effective nature simulation could be comprised of large projections of nature scenes accompanied by auditory stimulation (nature sounds or music) and nature smells. Even more effective might be a surround-projection of scenes or a surround video or video tour that mimics movement through a setting. Because of the relative ease of collecting images and video (when compared to creating computer simulations), the variety of settings would only be limited by data storage capacity. For maximal effectiveness, the simulations should be experienced in a private space (e.g., private crew quarters) that is free from other distractions.

Museums, visitor centers, amusement parks, and military training use a variety of methods, such as those described above, to create a sense of immersion and many of these methods may be adapted for capsule environments. Although an exploration of this literature and technology is beyond the scope of this review, it would be a useful avenue for further research on immersion methods and technology.

Dosage. There is very little data on how long and how frequent exposure to nature simulations needs to be in order to have a measurable effect. One meta-analysis of 10 studies explored the best regime of interacting with nature in order to improve self-esteem and mood (Barton and Pretty, 2010). Their results showed that the largest benefits appear to come from the first 10 minutes of exposure to nature, with slightly lower yet still positive returns for exposure up to 60 minutes. Although far from conclusive, these results suggest that more frequent shorter

exposures (i.e., under 60 minutes at a time) will have a greater impact in the long run than less frequent longer exposures – at least in terms of mood. Other studies of the restorative effects of nature over a longer period of time have found positive results with a nature intervention of 20-30 minutes per day, three days per week (e.g., Cimprich, 1993; Duvall, 2011). This level of exposure may provide a starting point for studies on optimal exposure to restorative nature simulations during long-duration spaceflight, but clearly more study is needed. In addition, it may be that directed attention and other mental processing recovery require longer or more frequent nature exposure than recovery from psychophysiological stress (Hartig et al., 2003).

Other considerations in determining the optimal dosage of immersive nature-based countermeasures are the restorative quality of the setting, the degree of mental fatigue and stress of the individual, and the intensity of environmental stressors to which one is chronically exposed. There should be flexibility in the scheduling of countermeasures so that exposure may be increased (if possible) in times of greater stress (for example, there is some indication that stress levels tend to rise during the 3rd quarter of a mission (Stuster, 2010).

Simulated window views. In addition to immersive nature experiences, research on window views and plants show that smaller and shorter interactions with nature can also provide restorative opportunities. In a chronically stressful environment, these micro-restorative opportunities are particularly important to help control stress and DAF in between longer immersive restorative opportunities. Although the research on the use of plasma screens as virtual windows is somewhat mixed, the data suggest that virtual windows can have psychological benefits and could be part of a countermeasure strategy for mitigating psychological risk in long-duration spaceflight. Simulated views would not only provide micro-restorative opportunities but would also foster a sense of connection with life on Earth.

As with immersive nature simulations, the content of the view will largely determine the effectiveness of virtual windows. A wide range of scenes would be appropriate and crew members could be provided with a variety of choices, including views from their Earth home or hometown, favorite parks and other landscapes, gardens, ocean views, and Earth from above views. In addition, it is likely that the more the screen looks like a window and not like a television mounted on the wall, the more effective it will be. More research is needed on how best to simulate realistic views, including type of technology (e.g., plasma screens versus back projected images). Using video to simulate views, rather than still images, is more memory intensive but has the advantage of offering dynamic stimulation. Displaying change at a real-time rate (e.g., slow changes in lighting, cloud movement, etc.) will keep the window view from becoming a distraction (e.g., drawing one's attention away from the task at hand) and avoid the problems described below with quick cuts in television and video games.

Plant production. Plants also provide important opportunities for micro-restorative breaks, as well as providing visual, tactile, olfactory, and possibly gustatory stimulation and providing a link with Earth. There also appears to be psychological benefits simply from the act of caring for a living thing. There is some indication that flowering plants have greater effects than foliage plants in terms of stress reduction (Kim and Mattson, 2002; Park et al., 2004), although the most

important factors appear to be the number of plants, their size, proximity to the person, and amount of exposure (Bringslimark et al., 2009).

Experiments with plant propagation in spaceflight show that a wide range of plants are capable of normal growth and full development in microgravity and that greenhouses in long-duration spaceflight are feasible (Sychev et al., 2008). The focus on plant propagation in spaceflight to date has necessarily been almost entirely on biological and technological factors (e.g., water and space needs, systems for root substrate regeneration), however, consideration should also be given to maximizing the use of plants as a countermeasure for psychological risk factors. In particular, visibility of plants is of paramount concern from a psychological perspective. This would ague for locating the greenhouse (or small garden) in a central area of the capsule and maximizing visibility of the plants within the chamber. It also argues for assigning and scheduling duties so that all crew members are able to interact with the plants throughout the mission.

Green exercise. Green exercise – combining exercise with a restorative natural setting – is another countermeasure that may be particularly effective in long-duration spaceflight. Because time is already scheduled for exercise, the nature exposure would not require additional time, and research indicates that the benefits of green exercise is greater than the benefits of either intervention alone. In addition, adding an interactive nature component to the exercise routine may increase motivation to exercise.

Pretty et al. (2005) studied the effects of exercise in conjunction with exposure to different types of environments. While exercising on a treadmill, participants were exposed to 30 scenes of either rural pleasant settings (largely nature), rural unpleasant settings (e.g., rusted cars in a field), urban pleasant settings (nature in an urban setting), or urban unpleasant settings. Another group exercised without exposure to any images. Results showed that although exercise alone had positive effects on blood pressure and measures of mental health, exercising along with exposure to nature (either rural or urban) boosted these positive effects. The additional benefits were greater for rural nature than for urban nature.

Studies on the use of VR in rehabilitation show that exercising in the context of a simulation can be more effective than other exercises in improving balance, gait disorders, and muscle movement and that much of the improvement can be attributed to increased motivation to engage in exercise (Bohil et al., 2011). Again, the technology does not necessarily have to be complex in order to be effective. Indeed, exercising in space while wearing VR goggles and hooked up to motion trackers may not be viable. A range of virtual walking, running, and cycling dvds exist for the commercial market and may provide motivation for exercise along with opportunity for mental restoration. Virtual environments can also be coupled with the exercise equipment to provide a more immersive experience. An example is Virtual Active's treadmill that uses videos of popular tourist spots, such as national parks, and matches the video speed to running speed and the treadmill incline to elevation changes in the video environment.

Meditating for mental restoration and stress reduction

Another potentially effective route to mental restoration and stress reduction is meditation (Kaplan, 2001; Slagter et al., 2007; Tang et al., 2007). Numerous studies show that meditation can lead to a reduction in physiological stress markers, including reduced levels of cortisol, epinephrine and other stress hormones (Wallace, 1970; Sudsuang et al., 1991; Gaylord et al.,

1989; Tsai and Crockett, 1993; Telles et al., 1995). There is also indication that the effects of meditation persist after the meditation period itself has ended. Regular meditation may inoculate one against future stressful situations by reducing the physiological stress response (Orme-Johnson, 1973; Mills et al., 1990). Other studies have shown that hypertension can be effectively controlled by meditation (Schneider et al 1995) and that meditators have an increased exercise tolerance and maximal cardiac workload as compared to non-meditators (Zamarra et al., 1996).

Meditation has also been found to directly impact the brain. Meditation is associated with significant changes in the brain hormone levels, nuerotransmitter levels, and blood, along with an increase in the alpha brain rhythms that are associated with restfulness (Bagchi and Wenger, 1957; Wallace and Benson, 1972; Jevning and O'Halloran, 1984; Glaser et al., 1992; Elias and Wilson, 1995; Newberg and Iversen, 2003). In terms of cognitive functioning, several studies support the notion that meditation improves cognitive task performance and increases one's ability to pay attention (Shapiro et al., 2008; Dhume and Dhume, 1991; Davidson et al., 1976; MacLean et al., 2010; Blasdell, 1973; Appelle and Oswald, 1974). In terms of general psychological well-being, meditation can result in increased happiness, freedom from anxiety, and increased vitality (Hjelle, 1974; Gaylord et al., 1989; Gelderloos et al., 1990).

Meditation is gaining traction in the military, both as a way to help soldiers recover from stress and, importantly, as a way to increase resilience, thereby improving functioning in stressful situations and reducing the risk of lasting psychological trauma. A study on the impact of meditation training (specifically a technique called Mindfulness) in the Marines, for example, showed that the soldiers who received training were more able to remain calm and focused in stressful situations and also recovered better from stressful training (Mockenhaupt, 2012).

Based on the research to date, meditation appears to offer many benefits in terms of addressing the stress, mental fatigue, and other psychological risk factors inherent in long-duration spaceflight. In addition, meditation requires minimal space (as long as the space has both visual and auditory privacy) and no special tools or technology. Many different types of meditation exist, each with specific philosophies, practices, and training (for reviews, see Goleman, 1988 and Shear, 2006). While it is beyond the scope of this review to recommend a specific type of meditation for use in spaceflight, all meditation techniques require some degree of training – training that would ideally be provided pre-flight. In addition, in-flight scheduling would have to allow for dedicated meditation time. Although recommendations vary considerably for the optimal amount of time one should spend in meditation, many fall in the range of 20-40 minutes at least once per day (although beginners generally start out with short session of approximately 15 minutes).

The non-restorative effects of television and video games

Although television and video games are full of fascination, they have not been shown to be restorative. In fact, quite the opposite – television viewing can lead to decreased energy and concentration and increased irritability; similarly, video games can leave one feeling worn out, dizzy, and nauseated (Kuby and Csikszentmihalyi, 2002; Singer and Singer, 2000). One explanation for these findings is that many television programs and video games aggressively capture attention through an abundance of content with hard fascination and though continual activation of one's orienting response (the instinctive reaction to sudden novel stimuli) through cuts, zooms, pans, and sudden noise (Reeves and Thorson, 1986; Rasmussen, 1973). Although these stimuli certainly provide an escape from the rest of the world, the constant state of alertness

from prolonged exposure to hard fascination along with continual activation of the orienting response can prove fatiguing. In addition, over the long term, escapism prevents the mind from engaging in much needed reflection which can contribute to overall levels of mental fatigue.

So although intense movies, video games, and other forms of escapism undoubtedly have a place in the spaceflight environment, they should be used judiciously and should not be relied upon to relieve stress and mental fatigue in the long run.

Providing Social Support

Current effective countermeasures for social isolation include communication with family and friends (through email and videoconferencing), extensive communication with others on the ground (e.g., celebrities, schoolchildren), resupply missions, care packages sent up with visiting crew, visual contact with Earth, and access to psychological support services from experts on the ground (Peldszus, 2011; Vakoch, 2011; Bluth and Helppie, 1986; Stuster, 2010).

With communication lags in longer distance space exploration, face-to-face real-time communication and gifts from Earth will not be possible and crew members will need to rely on onboard provisions and facilities and on themselves to a much greater extent (Kanas et al., 2009). Maintaining some level of communication with family and friends (e.g., through daily audio-visual messages that include reports on daily activities, updates on children, and well-wishes from home) will continue to be of high importance (Simon et al., 2011). Transmissions of current news, sports and entertainment programs, and other significant events on Earth (even if significantly time-delayed) will also help maintain a sense of connection with life on Earth (Gushin, 2002). Care should be taken in the content of transmissions, however, as receiving negative news about which one can do nothing can induce stress.

The use of virtual communities in tackling the problems related to social isolation has shown mixed results. Games on social networks, such as FarmVille, are hugely popular and appear to offer users a sense of community and connection with other players. Research on the effects of using social games and networking sites (e.g., Facebook) in terms of social involvement and psychological well-being, however, are mixed, with some studies showing positive effects and other reporting negative effects (Kraut et al., 1998; Hampton et al., 2009; Valkenburg et al., 2006; Young, 2009). Kraut et al. (2002) suggest that the data point to a "rich get richer" model where internet use and virtual community interactions are associated with positive outcomes for extraverts and those with more non-virtual social support and negative outcomes for introverts and those with less social support.

The general results on virtual communities sound a cautionary note for the use of social gaming and social networking in long-duration spaceflight. Also telling is Cacioppo and Hawkley's (2009) study suggesting that perceived social isolation has more to do with the quality of social interactions than the quantity. This result would suggest that spending significant time on relatively shallow social interactions (e.g., Facebook, Twitter, YouTube, Seek and other online sites and forums) will not be particularly beneficial (and, in fact, may be detrimental). Again, as with the discussion on increasing environmental richness and stimuli, the focus needs to be on meaningful, relevant, and engaging social interaction.

One particularly meaningful and important countermeasure for the risks associated with social isolation is regular private conferences between crew members and mission psychologists. Poynter (2006) writes vividly of the problems that occurred with lack of psychological support for the first Biosphere 2 crew, "I did not know how to pull myself out of the bouts of depression and I was afraid of losing myself in the mind-hammering flashbacks and the leaden blanket of negativity" (p. 235). Due to time delays in communication in long-duration and long distance spaceflight, conferences with support staff would rely more on delayed messaging than real-time interaction.

Additional social and psychological support could come from expert systems and virtual therapists. The "Digital Friend" is one such device being developed for use in long-duration spaceflight (Hoermann et al., 2008). The device is a decision support system that is designed to assess levels of stress and performance and offer feedback and advice. Other systems are currently being developed for the military, for example SimSensei (developed by Louis-Philippe Morency and Albert Rizzothe at the USC Institute for Creative Technologies (ICT)), is an interactive virtual clinical decision support tool that is able to recognize and identify psychological distress from multimodal signals (http://ict.usc.edu/prototypes/simsensei/). In the spaceflight context, such a system could relay the outcomes of virtual interactions to flight psychologists on the ground, who could then help direct the virtual therapist's continued dialogue. Similarly, Jacki Morie, also at ICT, leads research on avatar-populated virtual worlds that have applications to telehealth and social support. Such virtual worlds can help assess users' cognitive, psychological, and emotional states and can also help people develop strategies and techniques for dealing with problems and stress. For example, the Coming Home world, developed for post-deployment soldier support, provides training in a meditation technique called Mindfulness Based Stress Reduction (http://projects.ict.usc.edu/force/cominghome/).

One could also imagine expert systems that would incorporate video of real people. Gushin (2002) points out that in stressful situations, Russian astronauts prefer to have contact with former cosmonauts who have coped under the same kind of extreme environment and situations. A library of interviews with former space crew and other ICE explorers, embedded in an expert system, could provide flight crew with trusted opinions and advice as well as a connection to the larger spaceflight community.

Finally, countermeasures for the risk associated with social isolation could include strategies for providing crew members with a sense of connection to Earth. A sense of Earth time could be maintained through day-night lighting cycles and seasonal changes could be tracked through subtle changes in light color and through changes in virtual environments (e.g., simulated views out the window). The celebration of holidays and family members' birthdays, and the marking of other milestones will also help to keep crew members connected to home, family, and one another.

Fostering Group Cohesion and Positive Group Dynamics

Living and working in a restricted space with the same small group of people is bound to lead to some stress, friction, and social conflict. As stated previously, one of the most effective countermeasures for social monotony and confined space is the provision of private space where crew members can recover from social stressors. Positive group dynamics will be further supported through countermeasures in other domains, as negative group behavior is often caused or exacerbated through attention fatigue, stress, and lack of social and psychological support.

In addition, countermeasures can be employed to directly support group cohesion and positive group dynamics. To being with, training in effective communication and intercultural understanding should be included in preflight training. During flight, activities for fostering group cohesion include both passive and active group recreation (e.g., movie nights, watching sports events, passive and active group games). Games that encourage creative play and movement – for example role playing and virtual or augmented reality games – can foster group dynamics while providing sensory (visual, kinetic, auditory) and intellectual stimulation and may be particularly beneficial. Häuplik-Meusburger et al. (2010) for example, developed an interactive group strategy game specifically for use in microgravity. The game uses interlocking spheres and involves the strategic placement of game pieces.

Other games and activities that allow crew members to act outside their normal mode (for example, play acting, creative performance, mystery games or other activities and social simulations) may also help relieve social monotony and foster team building. In addition to recreation and games, communal eating and celebrations can help foster group cohesion. Toward the end of the disastrous first Biosphere 2 mission, celebrations around food were the only thing that brought the whole group together (Poynter, 2006).

In addition to team building activities, legitimate outlets for aggression, hostility, and frustration are critical in maintaining positive group dynamics. These outlets might include regular "bull sessions" or other group sessions (Palinkas et al., 2000). Competitive group games (e.g., the active partner games on the Nintendo Wii or Microsoft's XBox Kinect) can also provide an appropriate outlet for aggression and tension (Bachman and Otto, 2011). Blogging and writing in a diary may also be effective ways of dealing with social tension and solving problems (Boniel-Nissim and Barak, 2011). Some studies show that blogging not only helps people process their thoughts but also helps provide a sense of community and reduces their sense of isolation (Baker and Moore, 2008). Stuster (2010) similarly found that journal writing served as a powerful outlet for frustration. Astronauts wrote candidly in their journals and benefited from the fact that they knew someone was reading what they wrote (and also the fact that they retained anonymity from all but the psychologist analyzing the data). One astronaut wrote, "I often use this journal to vent my frustrations. This helps me collect my composure to deal with the situations" (Stuster, 2010, p. 56).

A SUMMARY OF COUNTERMEASURES

The long-duration spaceflight environment is marked by a host of significant psychological risk factors, including:

- Sensory reduction and monotony
- Visual and auditory distractions
- Lack of cognitive and behavioral support (e.g., in wayfinding, orientation, locating gear)
- Lack of control and autonomy
- Over scheduling/ overwork
- Lack of intellectual stimulation
- Social isolation
- Social monotony
- Lack of privacy
- Lack of opportunities for mental restoration and stress reduction

The significant and varied nature of these psychological risk factors means that there is no single countermeasure that will adequately mitigate risk. Rather, development of a risk management strategy should be from the perspective of building a portfolio. Countermeasures should include those directed at reducing environmental stressors through (1) capsule and mission design and (2) crew selection and training, and those directed at (3) assisting crew members in coping with and recovering from the effects of inherent stressors.

Within these three categories, the goals of specific countermeasures should be to mitigate the effects of environmental stressors by:

- *Reducing distractions and stressors* related to capsule design and mission planning.
- *Improving crew response to stressors in the spaceflight environment* through crew selection and training.
- *Stimulating the brain* though both through external sensory stimuli and intellectual stimuli, thereby helping to ameliorate some of the neural and psychological impacts of low sensory and monotonous environments.
- *Assisting in the recovery of directed attention and the reduction of overall stress*, thereby helping to maintain cognitive functioning and appropriate behavior.

- *Providing social support*, thereby helping to ameliorate some of the negative effects of social isolation.

- *Fostering group cohesion and positive group dynamics*, thereby helping to reduce some of the negative effects of social monotony and social interactions.

Given the constraints on mass, time, and energy inherent in long-duration space missions, focus should be on countermeasures expected to have the largest impact and those which simultaneously address multiple risk factors. The technology used in countermeasures should be maximally simple, robust, and flexible so that it could be repaired (or modified if necessary) during the mission. Equipment failure can not only render a countermeasure unusable, but can be a significant source of frustration and stress (Peldszus, 2011). In addition, countermeasures should be implemented at a variety of scales (e.g., micro and intensive mental restoration and stress reduction opportunities) and account for individual differences in interest and ability.

Tables 1 through 6 provide a high level overview of the countermeasures highlighted in this paper, along with an indication of which psychological risk factors each countermeasure addresses. (For more detail on recommended countermeasures, refer to the appropriate section in the text.)

Table 1. Designing the Environment and Mission to Reduce Stressors

	ENVIRONMENTAL STRESSOR								
	Physical Environment			Workload Incompatibility			Social Isolation and Monotony		Lack of Coping Mechanisms
COUNTERMEASURE	Sensory Deprivation and Monotony	Environmental Distractions (esp. Visual/ Auditory)	Lack of Cognitive and Behavioral Support from Environment	Lack of Control and Autonomy	Lack of Intellectual Stimulation	Overscheduling/ Overwork	Social Isolation	Social Monotony and Conflict	Lack of Envt Support for Mental Restoration/ Stress Reduction
Space for socializing			X					X	
Space for recreation			X					X	
Comfortable and efficient work space		X	X						
Private space/ sleeping quarters		X	X					X	X
Separation of spaces (physical and/or visual) with different functions		X	X						
Design to improve wayfinding and orientation	X		X						
Personalization of envt	X			X					
Control over envt (e.g., reconfigurable interior, temp, noise)	X	X	X	X					
Schedule time for recreation/ restoration						X			X
Appropriate work scheduling and time allocated per task				X		X			X
Reduce background noise (e.g., through noise reduction technology)		X							
Reduce visual clutter (e.g., improved stowage systems)		X							
Organized and accessible stowage			X						
Proper lighting levels and location			X						
Lighting for sleep/wake, connection to Earth time	X		X				X		X

Table 2. Selecting the Training Crew to Reduce Stress Response

	ENVIRONMENTAL STRESSOR								
	Physical Environment			Workload Incompatibility			Social Isolation and Monotony		Lack of Coping Mechanisms
COUNTERMEASURE	Sensory Deprivation and Monotony	Environmental Distractions (esp. Visual/ Auditory)	Lack of Cognitive and Behavioral Support from Environment	Lack of Control and Autonomy	Lack of Intellectual Stimulation	Overscheduling/ Overwork	Social Isolation	Social Monotony and Conflict	Lack of Envt Support for Mental Restoration/ Stress Reduction
Crew selection – appropriate personality/behavior traits					X		X	X	
Socially compatible crew							X	X	
Training for effective communication, intercultural understanding, conflict resolution								X	
Training for stress management/ coping skills							X	X	X
Mission/simulation experience									X

Table 3. Stimulating the Brain

	ENVIRONMENTAL STRESSOR								
	Physical Environment			Workload Incompatibility			Social Isolation and Monotony		Lack of Coping Mechanisms
COUNTERMEASURE	Sensory Deprivation and Monotony	Environmental Distractions (esp. Visual/ Auditory)	Lack of Cognitive and Behavioral Support from Environment	Lack of Control and Autonomy	Lack of Intellectual Stimulation	Overscheduling/ Overwork	Social Isolation	Social Monotony and Conflict	Lack of Envt Support for Mental Restoration/ Stress Reduction
Increase sensory stimuli (visual, auditory, olfactory, gustatory, tactile)	X								
Partial crew control/input over work and schedule				X	X	X			
Intellectually stimulating work					X				
Support for personal projects					X				
Intellectual stim during leisure (reading writing, puzzles, games, hobbies, play, creative expression, music/art, etc.)	X				X				
Physical exercise	X								X

Table 4. Providing Opportunities for Mental Restoration and Stress Reduction

	ENVIRONMENTAL STRESSOR								
	Physical Environment			Workload Incompatibility			Social Isolation and Monotony		Lack of Coping Mechanisms
COUNTERMEASURE	Sensory Deprivation and Monotony	Environmental Distractions (esp. Visual/ Auditory)	Lack of Cognitive and Behavioral Support from Environment	Lack of Control and Autonomy	Lack of Intellectual Stimulation	Overscheduling/ Overwork	Social Isolation	Social Monotony and Conflict	Lack of Envt Support for Mental Restoration/ Stress Reduction
Simulated immersive nature experience	X							X *	X
Window view/ simulated view	X							X	X
Green exercise	X							X	X
Plant production (e.g., visible greenhouse, spice garden)	X							X	X
Meditation					X			X	X
Sleep								X	X

* Mental restoration has an indirect positive effect on social interactions because social conflict is significantly more likely when people are stressed and/or mentally fatigued.

Table 5. Increasing Social Support

	ENVIRONMENTAL STRESSOR								
	Physical Environment			Workload Incompatibility			Social Isolation and Monotony		Lack of Coping Mechanisms
COUNTERMEASURE	Sensory Deprivation and Monotony	Environmental Distractions (esp. Visual/ Auditory)	Lack of Cognitive and Behavioral Support from Environment	Lack of Control and Autonomy	Lack of Intellectual Stimulation	Overscheduling/ Overwork	Social Isolation	Social Monotony and Conflict	Lack of Envt Support for Mental Restoration/ Stress Reduction
Communication with family and friends							X	X	
Transmission of current news, sport and entertainment programs, etc.	X				X		X		
Private conferences with mission psychologist							X	X	X
Support from expert systems/ software							X		
Celebration of holidays and milestones							X	X	

Table 6. Fostering Group Cohesion and Positive Dynamics

	ENVIRONMENTAL STRESSOR								
	Physical Environment			Workload Incompatibility			Social Isolation and Monotony		Lack of Coping Mechanisms
COUNTERMEASURE	Sensory Deprivation and Monotony	Environmental Distractions (esp. Visual/ Auditory)	Lack of Cognitive and Behavioral Support from Environment	Lack of Control and Autonomy	Lack of Intellectual Stimulation	Overscheduling/ Overwork	Social Isolation	Social Monotony and Conflict	Lack of Envt Support for Mental Restoration/ Stress Reduction
Passive recreation (e.g., movie nights)	X							X	
Active social exercise/ recreation (e.g., wii; bespoke games)	X				X			X	
Social-based mental challenges (e.g., play acting, creative group performances, mystery games and sims)	X				X			X	
Communal eating								X	
Blogging/ dairy writing					X		X	X	X
Outlets for aggression and hostility (e.g., bull sessions, group games and competitions)								X	

CONCLUSIONS AND NEXT DIRECTIONS

This review has summarized the evidence for the effectiveness of wide range of countermeasures for psychological risk factors in long-duration spaceflight and identified those countermeasures that we would expect to be particularly effective. Relatively little of these data, however, comes directly from studies in the spaceflight environment; rather, most of it is drawn from analogue ICE environments and from the broader environmental psychology literature.

Due to this lack data, more research is needed on the application and effectiveness of countermeasures specifically in long-duration spaceflight. In addition, more data are needed on space appropriate technologies for implementing specific countermeasures (e.g., simulated immersive nature experiences) and the feasibility of technologies being space ready in relation to the NASA Roadmap.

Gathering the perspectives and insights of relevant spaceflight experts is a useful starting point to identifying the most pressing research needs and the feasibility of specific technologies. This is the focus of the next section, which reports on an operational assessment based on interviews with a range of subject matter experts (SMEs).

Along with this additional research, thought should be given to the monitoring and measuring of mental well-being and psychological functioning during spaceflight. Such a monitoring system would not only provide NASA with useful data but could also be used to identify problems (e.g., in group functioning, stress levels, mental fatigue levels) in their early stages so that specific countermeasures (e.g., conflict resolution, countermeasures to restore directed attention capacity) could be initiated to help resolve problems before they become more serious.

3. Operational Assessment of Environmental Factors and Countermeasures related to Behavioral Health and Performance during Long-Duration Spaceflight

OVERVIEW

The broad literature and evidence reviews presented in the previous sections yielded significant information and insights regarding psychological and behavioral risk factors and countermeasures in spaceflight and analogue ICE environments. One finding of the evidence review, however, is that there is relatively little hard data on the application and effectiveness of countermeasures specifically in spaceflight environments, particularly with respect to behavioral and psychological aspects of long-duration and/or long distance spaceflight. In addition, questions remain regarding the applicability of specific countermeasure technology in the spaceflight environment. Because of these unanswered questions, it is important to go beyond the existing literature and perform an operational assessment, gathering insight directly from SMEs.

This operational assessment was designed to gather expert insight on: (1) environmental risk factors specific to long-duration and distance spaceflight; (2) current countermeasure technology and design (e.g., related to environmental modifications such as visual screens, virtual reality, onsite plant production, stowage systems to reduce visual clutter, in-flight support mechanisms in the context of communication delays, minimum requirements for and constraints on private space); and (3) issues related to countermeasure implementation (e.g., design constraints), including the feasibility of technologies being space ready in relation to the NASA Roadmap.

METHODOLOGY

Ten SMEs were interviewed individually by phone, with each interview lasting approximately one hour. An N of 10 was deemed adequate by the PI and a scientific merit review panel to capture the range of relevant areas of expertise (e.g., space psychology, spacecraft and ICE analog architecture, human factors engineering, human factors design). The interviews were conducted by the PI, Dr. Anne Kearney, and notes were taken by both Dr. Kearney and Diana Arias at NASA Johnson Space Center.

Experts

Participant selection was made based on: (1) high level of expertise in one or more of the identified areas and (2) sufficient coverage across the spectrum of desired areas of expertise. Participant recruitment and consent followed approved NASA-IRB procedures.

The ten SMEs who participated in the study included eight people from within NASA (both at the Johnson Space Center and the Langley Research Center) and two experts outside of NASA. The areas of expertise covered were: space psychology, spaceflight and exploration vehicle architecture, extreme habitat architecture, avionics systems architecture, space human factors engineering, adapting commercial technology for spaceflight, human systems interaction in space and other extreme environments, and NASA human factors related project and division lead management.

Interview Questions

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. Although a few general questions were asked of all participants, each interview was tailored to the expertise of the specific SME in order to maximize the amount of detailed information generated. Questions across the 10 interviews covered psychological stressors and countermeasures that emerged from the literature review and covered the following themes:

1. **Perceived stressors in long-duration spaceflight** (asked of all experts)
2. **Perceptions of most effective countermeasures in long-duration spaceflight** (asked of all experts)
3. **Capsule layout and architecture**
    a. Private space: perceived need for, minimum size, characteristics/design/layout
    b. Capsule layout
    c. Background noise: perceived stressor, technology/strategies for mitigating
    d. Visual clutter: perceived stressor, stowage systems design, other stowage issues
4. **Windows as countermeasures**
    a. Perceived effectiveness and acceptability
    b. Real vs virtual windows
    c. Appropriate technology
    d. Implementation (size, location, etc.)
    e. Constraints/ issues
5. **Virtual reality as countermeasure**
    a. Perceived effectiveness and acceptability
    b. Current and anticipated use of VR systems
    c. Use for “green exercise”
    d. Appropriate technology

    e. Constraints/ issues
6. **Plant propagation as countermeasure**
    a. Perceived effectiveness and acceptability
    b. Appropriate technology/ implementation
    c. Constraints/ issues
7. **Psychological support and communication**
    a. Communication needs and issues (particularly in context of time delay)
    b. Most effective types of psychological support
    c. Strategies for maintaining/providing support in context of long-duration missions
    d. Virtual support
8. **Crew selection and training**
    a. Crew selection: issues and requirements in context of long-duration missions
    b. Training for and during long-duration missions
9. **Planning and designing for countermeasures**
10. **Other countermeasures/ issues/ recommendations** (asked of all experts)

Analysis

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. Data are presented below by theme and have been aggregated across individuals, highlighting areas of agreement and instances where views differ.

RESULTS: EXPERTS PERSPECTIVES

The SMEs were in agreement that long-duration spaceflight has inherent environmental stressors that can have significant psychological and behavioral impacts. In particular, SMEs mentioned the risks associated with: social isolation, negative interactions among crew members and between the crew and ground, architecture and design (e.g., lack of privacy, layout of spaces, sub-optimal interface design and technology), lack of environmental stimulation, and concern over safety and security.

There was also agreement that a wide range of countermeasures are required to offset psychological and behavioral risk in spaceflight and that countermeasures have an increased importance in long-duration missions. In addition, long-duration missions, for example a mission to Mars, have specific characteristics that have implications for countermeasure design and implementation. In particular, SMEs mentioned:

Duration. Experts estimate that a mission to Mars, for example, would include a transit time of 4-6 months (depending on the technology used) with a stay at Mars ranging from 30-500 days. These long-duration missions have increased risk of psychological and behavioral problems, prompting one expert to comment that one of the best countermeasures to reduce risk is better propulsion systems and thus a decreased mission time.

Communication lag. Lags in communication, or possibly an absence of communication, may compound environmental stress and also make it more difficult to implement specific countermeasures, such as direct communication with family and friends.

Volume constraints. The International Space Station (ISS) may not be a particularly good analogue for a long-duration capsule not only because the mission duration tends to be shorter but because the volume and design may be luxurious in comparison to what is expected in a long-duration capsule. The constraints on volume and mass associated with a long-duration mission may mean an increase in environmental stress related to lack of privacy, sense of crowding, and a smaller work environment. Volume constraints also put constraints on the type of countermeasures that can be accommodated and experts pointed out that space engineers and architects are particularly interested in countermeasures with minimal volume and mass requirements.

Multiple phases. A long-duration mission may have multiple phases with different associated environments. The different phases of a mission to Mars, for example, will have different gravity environments, differences in the external view, differences in communication lag, and differences in objectives and workload. Each of these different phases will have different design considerations and possibly a different set of stressors and preferred countermeasures.

Technology considerations. Technology in space – particularly crucial technology – needs to be highly reliable. In a longer-duration mission, where the stress on technology may be greater and where there is no opportunity for re-supply, the robustness of technology is even more critical. Systems architects pointed out that we do not have enough information about whether current technologies (such as hardware, graphics processing units, visual displays) would last the duration of a longer mission, survive beyond low Earth orbit, or be affected by additional stressors such as the radiation from the Van Allen belt. These constraints and unknowns regarding technology may have implications for how to best implement specific countermeasures.

Although specific data on the psychological and behavioral risks in the context of long-duration spaceflight, like a mission to Mars or a near-Earth asteroid, do not exist, experts have no doubt that the risks are significant. Given the significant risks and the lack of high-fidelity data on specific countermeasures, flight psychologists agreed that long-duration missions will need to include a wide range and variety of countermeasures (for example, a suite of entertainment and communication options, virtual reality systems, psychological support options, and "green" elements) along with enough time in the schedule for the crew to avail themselves of these countermeasures. SME's views on specific countermeasure are provided below.

Capsule Volume and Layout

Although from a psychological point of view many experts felt that the more habitable volume the better, there was also recognition that from an engineering and fiscal point of view, the less volume and mass the better. SMEs note that the tension between desired and feasible volume highlights the importance of:

- Providing engineers with concrete recommendations in terms of, for example, volume of private space.
- Careful consideration of capsule shape (to maximize the volume to mass ratio) and layout (to maximize perceived volume and task facilitation).
- Designing and implementing countermeasures with minimal or lower volume and mass requirements.

With respect to volume-intensive countermeasures, the need for private space is perhaps the issue most on people's radar, although other considerations in terms of interior layout are also perceived as important.

Private space

SMEs agreed that adequate private space is essential on long-duration missions to enable crew to retreat and get away from one another. The importance of private space is found in analogues as well: for example, having adequate private space (including auditory privacy) was a top priority for winter-over crews in the design of Halley VI.

Characteristics of private space. The overall volume required for private space depends, in part, on the types of activities and tasks the space must accommodate. In addition to activities like sleeping and getting dressed, experts mentioned the need for crew to be able to work in their private quarters and to communicate in private with friends, loved ones, and support staff. There should also be adequate opportunity for personalizing the space with photographs and other memorabilia and for storing personal items.

Volume requirements also depend, in part, on the nature of the design, as good design can make a small space more functional and feel less claustrophobic. One space architect pointed to interesting models of small sleeping quarters that might provide design insights, such as Japanese hotels, sailboats, motor homes and other mobile sleeping and privacy accommodations. Several SMEs also mentioned the potential benefits of having windows (real or virtual) in sleeping quarters. For Halley V crew, having a window was more desired than having larger private quarters (and windows were indeed incorporated into the new station). The Russian side of the ISS is another example of a bedroom with a view.

Auditory privacy is also an important consideration in the design of private quarters. A survey of winter-over crews in Antarctica found that having better sound insulation between bedrooms was of higher importance than having a larger space (although the existing crew quarters were large by ISS standards). On Halley VI, this auditory privacy was achieved by pre-fabricating each bedroom and then packing the space between

individual structures with insulation. According to flight psychologists, responses from crew on the ISS indicate that the current level of auditory privacy in private crew quarters is adequate, although one human factors expert noted that some astronauts comment that vibration (the transference of movement from one sleeping quarter to another) is a problem.

Size of privates space. Although there was broad consensus on the need for private sleeping quarters – the experts unanimously agreed that an "open bunks" model would not be acceptable from a psychological standpoint – there was less consensus on how big private quarters need to be. Several experts did not feel they had sufficient data to offer a minimum volume for private space. Several others felt that the current volume of private quarters on the ISS (roughly two cubic meters per person) is adequate. One human factors engineer, on the other hand, argued that current volume in crew quarters is not adequate for a long-duration mission and that the volume of private space should be doubled and then an additional buffer added. One way to get this additional volume would be to add other functions to the private space, for example using the space for more donning and doffing of clothing, to accommodate long-term medical care (as opposed to a separate medical space), and to accommodate certain types of exercise.

None of the SMEs recommended smaller private spaces than the current ISS quarters, although again, several did note that we do not currently have enough data to determine minimal acceptable volume.

Privacy outside of private quarters. Several SMEs noted the need for semi-private space outside of crew quarters. There is a need for space where a crew member can privately engage in activities, movement or behaviors that let off steam without fearing looking silly or disturbing others. This does not necessarily need to be a separate space for each crew member; rather it could be a semi-private space away from the main flow of activity. The desire for semi-private space was also one of the priorities for Halley V winter-over crew and hence a reading/quiet space was designed into Halley VI.

The need for privacy in other contexts – particularly work and hygiene – was also noted. One expert noted that the need for work privacy has implications not only for the placement of work stations but also for the scheduling of tasks, so that people are not working on top of each other in space and time. Privacy in hygiene (toilet, shower) may be increased by strategic location of hygiene facilities (e.g., placing them near noisier areas to help achieve auditory privacy). On Halley VI, sense of privacy in bathrooms and showers was increased by including a threshold zone (a small space with a window) before the entrance to the shower/toilet. Having these facilities set back from the main corridor gives them a more protected feeling.

Other space and layout issues

Communal space. There was widespread agreement among SMEs that although private space is a necessity, it cannot come at the expense of communal space. Communal space is necessary not only to complete group tasks and activities, but to build team cohesion, promote interpersonal interaction, and decrease one's sense of isolation. How much communal space is needed? One human factors expert recommends designing in roughly the same amount of communal space as private space. He and others note that communal space needs to be multi-use and should accommodate a range of activities, such as eating,

playing games, group meetings and planning, lounging, and more. The required volume of the communal space or spaces will depend on the volume envelope for the different tasks and equipment that it must accommodate but should be large enough to accommodate the entire crew in relative comfort (so that, for example, crew are not having to float/climb over one another).

Work space. Both a study of Skylab and data from HERA (Habitability Exploration Research Analog) indicate crew preference for the separation of work, rest, and communal areas. In the context of HERA, the "work area" also includes medical and exercise areas and is separate from communal space and private space. In addition, putting the hygiene area next to the work area was found to be an acceptable layout. The volume needed for the work area is very much dependent on the work and equipment requirements of the mission, but again the volume (and work schedule) must be large enough to complete work tasks without being too cramped. Short duration analogues have shown that packing too much into the work space makes for a very frustrating (and hence inefficient) work environment.

Interior layout/configuration. Is there an optimal layout for a capsule interior? Configuration options depend on the architecture of the capsule (e.g., a stacked "hockey puck" design versus a horizontal design similar to the ISS). Within the constraints of the architecture, some of the issues that should be considered are:

- Separation of work, communal, and private space
- Separation of "dirty" (e.g., hygiene, eating) and "clean" (e.g., recreation, medical) areas
- Separation of "noisy" (e.g., work, exercise) and "quite" (e.g. sleeping quarters, semi-private space) areas
- Translation spaces. Translation paths are not only necessary to facilitate movement but can also provide a sense of separation and visual privacy between spaces. Effective use of translation paths or thresholds (along with color shifts) can encourage the perception of a series of interconnected destinations rather than one long corridor. The thresholds themselves can also provide an opportunity for micro-restorative opportunities. In Halley VI, for example, thresholds between modules have windows, which provide an opportunity to see onto the ice. Similarly, in HERA, plants were placed between the decks, so that every time crew changed decks they had visual access to the plants.

Designing for flexibility and control

Crew needs and desires regarding interior configuration and design can shift over the course of a mission and these potential changes should be taken into account, as much as possible, in design. For example, several SMEs noted that sexual relationships may form during long-duration missions and that some accommodation should be made for this. (The current size of ISS sleeping quarters is not large enough to accommodate a couple.)

Others noted that at some point in the mission, crew members may prefer shared sleeping quarters, not because of a sexual relationship, but for the feeling of security that can come from having someone sleeping nearby. Antarctic winter-over crew members, for example, often look forward to sharing their room with someone else during the summer months – it offers them a change of pace and some social interaction while, at the same time, they know it is for a limited amount of time.

Work space requirements may also change over the duration of the mission as work objectives and equipment requirements may be different for different parts of the mission. In addition, the different requirements for different gravitational fields (e.g., in transit versus on a planetary surface) also have implications in terms of interior configuration.

Several SMEs indicated that inflatable partitions, inflatable habitats, or other flexible designs may offer some ability to reconfigure space as needed during a long-duration mission. One expert pointed out that the study of different cultures and dwelling types (e.g., Japanese interiors, nomadic dwellings, slums, military encampments) may offer additional insights on small space flexibility and reconfigurability.

The need for crew to have the ability to control and modify their environment in other ways over time was also noted (e.g., reconfiguring wall panels, changing color, changing lighting and putting up curtain and partitions). Building in changeability and flexibility not only enables crew to meet changing needs, but also contributes to meaningful environmental complexity, which is desired from a psychological point of view.

Interior Design

Stowage

The visual clutter related to stowage, cables, wires, etc., is perceived as a problem in part due to the compelling images of the visual disarray on the ISS. As several SMEs point out, however, clutter is not a problem for everyone. Organizational preferences and the ability to cope with clutter are, in part, personality traits. For people who tend to be fastidious, the chaos of the ISS may drive them to distraction while others are able to function well in that type of environment as long as they understand the organization system and are able to find what they need when they need it.

Despite different individual tolerances for clutter, there is agreement that disorganization is a problem both in terms of psychological health and in terms of work safety and efficiency. SMEs noted that stowage systems need to:

***Facilitate finding tools, equipment, food and other items*.** Crew need to be able to quickly and easily find what they need when they need it. There are implications here both for physical storage systems and for inventory control procedures and training.

***Be flexible*.** As several SMEs note, stowage has a life space. Supplies get used up and stowage compartments may empty over the duration of the mission. In order to avoid un-used or wasted space, stowage systems need to be flexible so that they can be

reconfigured as stowage needs change. Moving from hard racks to soft stowage of different sizes (that can be folded flat and stored away when no longer needed) has been one way to increase the flexibility of stowage space on the ISS and reclaim space when no longer needed for stowage.

***Address the issue of trash*.** Although some space can be reclaimed as supplies are used up, one expert pointed out that the rate of reclamation is relatively slow because as supplies are consumed, trash is generated and that trash is typically not stored as efficiently as the original supplies. Packaging related to food or logistics is a significant portion of the volume of stowed items on the ISS and that clutter could be greatly reduced through improved trash storage and compaction systems and through re-using packaging materials for other things (e.g., visual partitions or furniture). Trash accumulation is a significant issue (in terms of volume, toxicity, off-gassing, and odor) that should be studied more.

Lighting

There is recognition that lighting levels need to be adequate for work and other activities and that there may be physiological and psychological value to being able to change the color and temperature of lighting. The Flight Deck of the Future project, for example, is looking at ways that changing the lighting color/temperature can help the crew to wind down. Lighting color and levels could also be linked to caution alerts: for example, the light might get brighter or change color in order to draw attention.

Noise

Noise cancellation or muffling technology is necessary so that crew can have a break from excessive ambient noise and can also have auditory privacy from one another when desired (e.g., in private quarters). There is anecdotal evidence that current noise levels on the ISS are acceptable. Although flight psychologists do not ask specifically about noise levels they do not generally receive complaints about noise from ISS astronauts (although the lack of complaints does not necessarily indicate that there is no impact in terms of work efficiency, etc.).

Several SMEs also mentioned that while noise can be a stressor, there are also potential benefits of meaningful or masking noise. For example, ambient noise can provide some auditory privacy from hygiene areas, noise can be used as part of a warning or alarm system, and changes in ambient noise can alert crew to potential problems.

Interface design

Good human-system interface design can reduce stress from information overload while providing timely and useful information. Crew members will have different informational needs during a long-duration mission and this has an impact on the types of interfaces (e.g., visual and auditory displays) that will be the most appropriate and useful. Long-duration missions will, for example, have longer quiescent phases than dynamic phases and there will be a corresponding shift from controlling the vehicle to monitoring it. This may mean that crew will need to access information at a higher and more intuitive level, which may mean moving away from traditional displays and toward using gesture,

touch or voice-based interface designs. There will also be communication lags with ground control and possibly periods of no communication, which would mean that crew will need to have greater on-board access to information.

The Flight Deck of the Future project is currently working with an outside company to develop technology that would allow crew to access and interact with 3-dimensional graphical information. Another example of interactive display technology that is currently being explored by the project is an interactive 42" screen developed by Microsoft (and currently called Pixelsense) that could either hang on the wall or could be used as a table surface. Screen surfaces such as this could provide a communal interactive table which could be used for a range of activities based on viewing and interacting with information – from planning missions to playing communal games.

Increasing environmental complexity

A number of SMEs mentioned the importance of increasing environmental complexity in order to stimulate the senses, provide a more pleasurable place to live, and maintain psychological health. In the design of Halley VI, architects put a priority on increasing sensory stimulation through design. They achieved this in three main ways: 1) use of windows and light (to maximize natural spectrum light and views of the external environment) 2) use of color throughout the modules (colors were selected for the different modules and activity areas by a color psychologist) and 3) incorporating natural materials where possible (for example, using Lebanese cedar on a central spiral staircase both for aesthetic reasons and because it has a pleasant natural aroma). Other SMEs also talked about the importance of environmental stimulation, particularly of stimulation (e.g., colors, sound) that is meaningful to humans.

Several SMEs noted that smell is an important stimulus that may be used as part of a warning system, to enhance the taste of food, and also as a pleasurable stimulus in its own right. One expert was involved in a study that made 10 different identifiable "edible" fragrances (e.g., basil, lime, cocoa, pepper) available to crew in an analog environment. Initially, crew members were uninterested in the fragrances, but once they tried them, they found them quite enjoyable. Some of the concerns with olfactory stimulation are determining how to select, store, and disseminate the smells and also how to scrub odor molecules out of the atmosphere. There is also the issue of changing preferences over time – the aromas that crew find pleasurable at the beginning of the mission may no longer be preferred later in the mission.

Countermeasures for Coping, Recovery, and Stress Management

Recreation and exercise

Flight psychologists noted that some of the most important countermeasures, other than communication with the ground, are recreation-based internal resources, such as music, videos, movies, books, musical instruments, and other types of recreation. The concepts of choice and variety are very important here as different crew members will have different interests and there is a risk of getting bored with the entertainment options over

the course of a long-duration mission. In addition to these traditional recreation-based countermeasures, a number of other important countermeasures were discussed:

Windows

Windows, both real and virtual, received overwhelming support from the SMEs interviewed. In addition, their perception is that the support for windows is widespread among the spaceflight community.

Real windows. Although there was awareness that decisions regarding the presence, placement, number and size of real windows will be driven largely by mission requirements, many SMEs talked about the value of real windows from a psychological perspective. Crew members strongly desire real windows, particularly if you can see something out of them. But will there be something to see during, for example, a mission to Mars? Although many make the comment that windows are not as important during such a mission because there will be little to see, one expert questions this assumption, noting that crew would have a view at the beginning and end of the mission and that the starfield view during transit, although it won't change rapidly, may take on greater significant for crew members, particularly if they have an interest or training in astronomy. Other SMEs also note that there is a significant benefit to having a real and unmediated view of the external environment: such a view, even if it is limited, offers of sense of perspective and can ground one in reality. As one expert noted, on a mission to Mars the moment that the blue dot of the Earth disappears will be a defining moment in history and would not be the same if experienced via a screen.

It was also noted that the more the windows allow for immersion in the external environment, the better from a psychological perspective. This sense of immersion was achieved on Halley VI by designing large (approximately 2' x 2'6") bedroom windows that were rounded at the top and bottom so that one almost gets the sense that they are outside. The Cupola, on the ISS, is another wonderful example of a window that offers an immersive experience.

Despite the benefits of real windows, SMEs note significant constraints, including: cost, structural integrity, and issues of gas penetration.

Augmented reality. Several SMEs talked about augmenting real windows with virtual views of the external environment: for example, the view from a robotic arm, a view of a different orientation, views of the planetary surface, or the view from space looking back at the capsule. The Flight Deck of the Future project has been exploring technology that would augment real windows by providing a real time view but at a larger size or by surrounding a real window with virtual windows to extend the view. At present, however, there is a technology gap in terms of stitching together real time video.

Virtual windows. There was widespread support among the SMEs for virtual windows. SMEs also felt that virtual windows have a great deal of support from the broader space community based on their perceived psychological benefits, the fact that they do not have significant volume and mass implications, and the ability to use virtual window screens for a range of other purposes (e.g., training, video conferencing, distance learning, and movies). The benefits of using virtual windows for both passive and immersive

experiences were noted, as well as the range of images that would be beneficial – for example, webcam views of favorite places on Earth, virtual views of cityscapes, nature scenes, and other meaningful places. Flight psychologists note that having views of meaningful places on Earth not only helps crew stay connected to Earth but also helps facilitate re-entry upon return to Earth.

Several important considerations regarding virtual windows were noted:

Size. There was agreement that larger screens are generally better, from a psychological point of view, as the experience of the virtual view is more engaging and immersive. The use of virtual scenes on Mir, for example, were well received but they did not get rave review largely because the images were small and relied on old technology (displays on computer screens) and were therefore not particularly engaging. The virtual windows project in HERA, in contrast, used a surround 4' x 8' screen in the common area, and crew greatly preferred the large images to those on laptop screens.

The problem with large screens is that they require a significant amount of real estate, which can be difficult to find given other competing demands for space. Part of the solution may lie in using flexible screens that could be easily set up and removed or using smaller screens which would be easily stored and tiled together as needed (discussed in more detail below).

Technology. There is a sense that the technology for virtual windows (whether screen or projected images) is available now and would certainly be ready, with any needed modifications, within mission time frame. Achieving perspective change (changes in view as if one was actually looking out a window from different angles) is still somewhat of a challenge, particularly when aligning virtual views with real window views. Prototype technology does exist, however, and is coming largely from the gaming community.

Location. In terms of where virtual windows should be located, there was support for including them both in common areas and in private quarters. Crew of analog environments (e.g., the Haughton Mars Project) have indicated a greater preference for virtual over real windows in private quarters because the virtual windows would allow them to have many different real time views and, in addition, could be used for other purposes, such as communication, training, and videos.

Virtual reality

There was widespread agreement that virtual reality systems, particularly virtual nature, would be extremely beneficial on long-duration missions. One flight psychologist pointed out that crew members on the ISS currently spend a large amount of time gazing down at the Earth from the cupola because it is particularly soothing. On a mission to Mars or other long-duration mission something will be needed to replace this. And although there is a perception that planners will endorse countermeasures based on virtual reality technology, experts point out that for planners to fully endorse virtual reality systems, we need more research to determine how effective virtual reality is for

maintaining psychological health in the spaceflight environment and how best to implement it.

The main perceived psychological benefits of virtual environments are relaxation and restoration (getting away/taking a break) and helping to stay in touch with things at home and recall what is waiting at the end of the mission. In addition, a number of experts mentioned the benefits of combining virtual reality with exercise in order to promote physical activity (e.g., running along a virtual nature trail). There was also widespread agreement that virtual reality systems could be effectively used for "just in time" training, for example to review procedures and operations needed at the destination or to learn medical procedures when needed. This type of training is perceived as particularly important in the long-duration context because it is simply not possible to train a crew beforehand on everything that may arise and because the time from initial training to when the skill is needed can be quite long.

Several issues specific to the implementation of virtual reality systems in the spaceflight environment emerged:

***The importance of immersion*.** For virtual environments to be maximally restorative, they need to create a sense of immersion, or the feeling of really being in the environment. Sense of immersion can be increased by engaging all of the senses, by good image resolution, and by the size and or sense of surround of the image. The Virtual Windows project on HERA, for example, combined large images with motion tracking technology to create an immersive environment in which people could "move." One of the experts involved in the project noted that all the astronauts who tested the environment thought its primary use would be to offer psychological comfort on long-duration missions.

***Appropriate technology*.** The technology discussed for creating virtual environments included flat screens (preferably surround – like a 360 degree movie theater screen – or at least on three sides), projection (again, ideally on a surround screen), holographic technology, and head mounted displays (e.g., goggles or helmet). The perceived value of a head mounted display system is that it would require less space in the capsule (both in terms of storage and while being used) and would possibly be more immersive. A potential drawback noted by some, however, is that crew might feel encumbered or overly confined with equipment on their head. More research would be needed to determine how to maximize the immersive experience and how crew would react to the different technology options, specifically in micro-gravity.

***Constraints*.** What makes sense on the ground in terms of technology may not make sense in space. One expert, for example, questioned the feasibility of launching large screen displays because of concerns about mass and the ability of the screen to withstand the force of take-off. Another constraint on screen size is the limited amount of surface real estate. Based on competing needs for interior surface area, it is unlikely that a large portion of wall space could be dedicated to a screen or screens. The one exception may be in private quarters, and several SMEs mentioned that private quarters may be a good location for dedicated screens or virtual reality systems.

One suggested solution to the problems with large screens was to use smaller, removable, screens that could be tiled together in different configurations as needed and stowed away when not in use.

Additional research would be needed to determine the volume required to engage in virtual reality-based activities, both in terms of equipment set-up (e.g., surround screens) and in terms of movement envelopes.

Plants and gardens

There is consensus among the SMEs that plants and gardens would be highly beneficial from a psychological point of view, highly desirable from the crew's point of view, and highly accepted by mission planners. The perceived benefits of plants include: visual and olfactory stimulation, psychological benefits from taking care of and interacting with plants, maintaining a connection with Earth, possible supplementation of oxygen supply, and contributions to the food supply. Given the mass and power needs for growing food, one expert noted consensus among mission planners that meeting significant food needs through fresh food growth is not feasible in the 30-40 year time frame. However, growing spices, herbs and other foods to augment the food supply is considered highly feasible.

Several issues emerged related to the implementation of gardens in the capsule environment:

***Encouraging interaction*.** For plants to be maximally effective from a psychological point of view, crew must be able to see and interact with them. The garden area on HERA, for example, was much more effective when placed between decks (where crew regularly passed them) rather than in a corner. Many SMEs advocated having plants or gardens in the common area/s, particularly the galley where they would get good visual attention. Other suggested also having plants in private quarters – either as real plants in growth boxes or, as one expert suggested, a virtual view of plants, so that one could call up the "plant channel" on the screen in order to see how the greenhouse plants are doing. Encouraging interaction with plants also means that caring for the plants should not be completely automated and that crew should share responsibility for tending the plants.

***Technology and size*.** There was agreement that existing technology, particularly recent hydroponic advancements, makes it feasible to have greenhouses in the capsule environment. It was also noted that greenhouses do not need to be too large to be effective. The garden on HERA, for example, consists of eight bays, each roughly 18 inches long and 10-12 inches deep. Similarly, one expert noted that the garden used in a 91-day analog test was roughly the size of a dormitory fridge (with a transparent front window) and that it provided a focal point for crew. Another expert envisions a "green wall" that would be roughly 5-6 inches deep and could line the walls along the side of a rack in the galley where it would be highly visually accessible.

***Constraints*.** Several challenges to growing plants in spaceflight were mentioned, including:

- Creating an environment where plants can thrive without adversely affecting other systems (e.g., humidity control, atmospheric gas composition).
- Choosing lighting wavelengths that are healthy for both crew and plants.
- Understanding the psychological impacts if plants die or a garden fails.
- Considering the feasibility of plant diseases and how this may impact the environment.

Food

Several SMEs mentioned the importance of food in spaceflight. Food can be a significant stressor – according to flight psychologists, the most common environment-related complaints from ISS crew have to do with food (either disliking the offerings, finding it unpalatable, feeling that there is not enough, or disagreement between crew and ground over what should be consumed) – and it can also be an effective countermeasure (e.g., care packages filled with snacks and other foods not available in the day-to-day diet; using the preparation of food for relaxation and social time).

Food will likely become a heightened issue in long-duration spaceflight as the diet is more likely to become monotonous, food preferences may change over time, and resupply from Earth will not be possible. One expert questioned whether the care package idea can be implemented in long-duration missions, possibly by pre-staging supplies for collection along the way or on the destination surface. The increased important in long-duration missions of personalizing food, based on type and portion preferences, was also mentioned.

Other countermeasures

***Pets*.** Several SMEs mentioned the possible psychological benefits of having small onboard pets, for example mice or fish.

***Meditation*.** Meditation was also viewed as a possibly effective countermeasure in long-duration spaceflight. Flight psychologists feel that the crew would be very open to it, particularly if there are proven benefits.

Crew Interaction and Management: In-Flight

Communication and social interaction

Contact with people on the ground is seen by flight psychologists as the most important countermeasure for maintaining psychological and behavioral health. Particularly important is communication with family and loved ones. Currently on the ISS, the most effective means of communication are through IP phone, video conferencing, and email. Although maintaining real time communication, as much as possible, will be critical on long-duration missions, the communication time lag means that other forms of communication and social interaction will become increasingly important. Several SMEs

noted that there is a point at which the time lag in communication becomes so great that it is simply not worth the investment of time and emotional energy.

When real time communication because untenable, crew will need to rely on time-delayed communication (e.g., email, Facebook, recorded video) and on pre-packaged communication (e.g., packaged training modules, interaction with a virtual doctor). One flight psychologist noted that it will be beneficial to put crew in touch with as many people as possible in order to provide a wide range of opportunities for social interaction. Crew members may, for example, teach a course from space, with time-delayed interaction with students, or they may work on an advanced degree while in space, with time-delayed interaction with professors. In many of these scenarios, the capability to both view and produce videos will be critical and there is a need for multiple on-board video cameras in case one fails.

Another idea mentioned by one of the flight psychologists is the possibility of involving family members in training videos, for example by having them deliver the training content. These videos, which would be packaged pre-flight for use in-flight, would not only provide just-in-time training but may be more engaging for crew and would provide an additional way of connecting with family members remotely.

Psychological support

Psychological support will be important on long-duration missions, with regular check-ins between flight psychologists and crew (although likely not in real time). In addition, any psychological support that is more autonomous will be beneficial. Virtual methods for interacting with a mental health clinician are currently in development: the system would be able to answer questions, diagnosis complaints and problems, and provide treatment recommendations.

Work and scheduling

There is a significant risk of boredom and of the psychological and behavioral consequences of boredom on long-duration missions. Engagement with meaningful work was perceived as critical by flight psychologists, with the sense that it is better for crew to be pushed toward being too busy rather than not busy enough.

In terms of the scheduling of work and other tasks (e.g., exercise, food preparation, leisure activities and sleep) several important considerations emerged:

Scheduling to reduce conflict. Careful scheduling (in terms of time and location) of tasks carried out by the different crew members can reduce sense of crowding and interpersonal conflict.

Scheduling autonomy. Although the current ISS model is that things are run from the ground, there is agreement among flight psychologists and other SMEs that crew on a long-duration mission will need to be much more autonomous in terms of how they schedule their time.

Programmatic input. There was support for the notion that crew should be involved in decisions related to the mission – from the science undertaken, to food choices, to capsule design.

Crew cohesion

The importance of fostering and maintaining positive crew interactions was mentioned by several SMEs. On Halley VI, for example, celebrations and other bench marks are seen as critical for the maintenance of the winter-over crew's psychological health and social fabric (e.g., the traditional week-long mid-winter celebration that includes performances and special banquets, celebrations for the last day of sun and the return of sun).

Crew Interaction and Management: Pre-Flight

Crew selection

Flight psychologists believe that crew selection is a critical issue in long-duration missions. Good relationships among crew members help provide a buffer against environmental stressors. On the other hand, problems among crew members, in terms of personality clashes, lack of team cohesion, or an inability to work together effectively, can be major stressors.

Without a specific mission to respond to, it is not possible to identify ideal crew characteristics, although there is agreement that individuals particularly suited to long-duration missions would differ somewhat from those selected for current (shorter duration) missions. Successful 6-12 month fliers tend to be less egocentric, more socially adaptable, and able to easily move between leadership and follower roles. Necessary core competencies on long-duration missions will include the ability to acknowledge mistakes, stand one's ground when needed, draw boundaries, find compromises, understand team norms and work consensually.

An important part of crew selection will be appropriately communicating expectations beforehand, both in terms of the duration of the mission and in terms of the mission characteristics, such as delayed communication and habitable volume. Volunteering with full knowledge and acceptance (on the part of the individual as well as their family members) is perceived as a significant indicator of readiness.

In terms of crew size, flight psychologists indicated that a crew of 4-6 people is preferable. If there are fewer than four crew members the relationships tend to be less stable, and if there are more than eight the group does not work as well together. In addition to crew size considerations, there was agreement that crew on a long-duration mission would need to have some input on the selection of their fellow crew members.

It is also important to note that although crew selection was seen as a critical countermeasure to environmental stressors, it was just one of many important countermeasures mentioned. Flight psychologists agreed that even the most careful crew selection would not mitigate the need for in-flight countermeasures.

Training

Flight psychologists feel that training will need to be done differently for long-duration missions. Team training (including experiential training), for example, will take on increased importance, both in terms of providing information for crew selection and also for increasing group cohesion once the crew (primaries and backups) have been selected.

The perception is that analog experience for at least 6 - 12 months will be required for crew selection. Additional training would then be needed for the selected team. Training cannot be so long that people are burned out before beginning the mission and one flight psychologists' best guess is that a year of training in an analog environment (e.g., Antarctic station, space station analog, or other analog) would be necessary and sufficient. The ISS, with its relatively large volume, instant communication, and other amenities is not perceived to be a particularly good analog for long-duration missions.

Longer-duration training is not only important from a skill development and team building perspective but also in terms of developing the expectations of family members and increasing crew members' understanding of the types of support mechanisms and countermeasures that work best for them in terms of maintaining psychological health.

In addition to ground-based training, several SMEs note that long-duration missions will require inflight training. Astronauts are typically high achievers with high standards for themselves and can feel considerable stress in long-duration missions from trying to remember ground-based training related to specific tasks and procedures. Provisions must be made for pre-packaged on-board training refreshers and "just in time" trainings.

CONCLUSIONS: SPACEFLIGHT DESIGN FOR PSYCHOLOGICAL HEALTH

To summarize, the SMEs interviewed for this project felt very strongly that a wide range of countermeasures would be necessary to maintain psychological and behavioral health in long-duration spaceflight. The primary countermeasures discussed were:

Social Interaction and Support

- Communication with ground (particularly family and friends). Strategies for facilitating communication and encouraging social interaction must be adapted for long-duration spaceflight and may mean an increased reliance on time-delayed communication and pre-packaged communication.
- Psychological support, both time-delayed (with flight psychologists) and virtual (with a virtual doctor or support person).

Capsule Design and Layout

- Private quarters, with recommended volume ranging from that currently on the ISS (roughly two cubic meters) to over twice that. Quarters should be designed to accommodate a range of activities including sleeping, private communication, and work.
- Semi-private space for quiet activities or smaller gatherings.

- Communal space large enough for the entire group to gather in relative comfort and able to accommodate a range of activities such as eating, planning, and playing group games.
- Separation of spaces so that noisy activities do not intrude on quiet ones, and areas perceived as messy are separated from areas perceived as clean.

Views and Interaction with Restorative Environments

- Windows, both real and virtual. The larger and more immersive the better. Appropriate technology for virtual windows exists and/or would be ready within mission time frame.
- Virtual reality systems offering immersive nature and other experiences. More research is needed on the most appropriate type of technology (e.g., screen versus head mounted device) and how best to implement that technology in the spaceflight environment.
- Plants/gardens in areas where they can be easily seen/ interacted with. Appropriate technology currently exists.

Interior Design

- Organized and flexible stowage system and inventory control procedures.
- Lighting at adequate levels and with changeable color/wavelength to help facilitate restfulness or wakefulness.
- Sufficient noise cancellation/ muffling. Anecdotal evidence suggests that the level of noise reduction on the ISS is acceptable.
- Interface design to reduce information overload and facilitate interaction with data.
- Increased environmental complexity (e.g., color, lighting, smell, natural materials, reconfigurability of environment).

Crew Selection and Management

- Sufficient meaningful work.
- Careful crew selection (with an ideal crew size of 4-6 people), with an emphasis on characteristics associated with success in long-duration missions, including ability to work with team and ability to find compromises. Some crew member input on crew choices.
- Extended training, including team training, and sufficient (i.e., one year) analog experience.

Other Countermeasures

- Traditional in-flight entertainment options, such as movies, books, musical instruments, etc. These have been very important countermeasures in spaceflight and will continue to be so on long-duration missions.
- Food variety and choice.
- Others countermeasures such as pets and meditation (although these have not been extensively explored in the spaceflight environment).

In addition to the general agreement on the critical nature of countermeasures in long-duration spaceflight, there was some frustration expressed over the difficulty in getting countermeasures integrated into the final vehicle design. Several SMEs perceive that engineers have not taken full advantage of good design and that some potentially

important countermeasures get lost in the shuffle of the design process or fall out of the picture because of budgetary constraints. Several solutions to the problems with integrating countermeasures into design emerged:

Take a Human-Centered Design Approach

Many SMEs noted the need for a more human-centered design approach. Such an approach was the cornerstone of the design for the Halley VI Antarctic Station. Before design began, Halley V winter-over residents were surveyed to assess what they did and did not like about Halley V and what attributes were most important to them in the new design. In addition, throughout the design process, architects did mental imaging exercises focusing on a "day in the life" of residents – What would they be doing from the moment they woke up? How would they want to feel? What design elements would support their work and make the spaces stimulating and comfortable? What routes would they traverse? What should their experience be of transitioning from one space to another? What are the opportunities for social interaction and for privacy?

SMEs noted the benefits of involving crew members, particularly those with flight experience, early and often in an iterative design process. Certainly, as one expert pointed out, re-design and development becomes much less likely in later stages of the planning and design process because of cost constraints. It was noted by several experts that good design is not a luxury nor is it necessarily expensive – it is a matter of taking human requirements into account at the beginning and then following a human-centered design process.

Facilitate Communication between Scientists and Engineers

Several SMEs mentioned that part of the problem with integrating countermeasures into design lies in communication gaps between mission planners, space architects, engineers, and scientists. In order for countermeasures to be accepted and integrated, the entire space community needs to recognize their value. In addition, the more tightly countermeasures are tied to issues that engineers care deeply about (such as safety and risk mitigation) and the more that the effects of countermeasures on risk can be quantified, the more acceptable they will be. Several experts noted that researchers must provide engineers with the information needed to make trade-offs, for example laying out minimum acceptable and ideal volumes for private space and communicating the benefits of the additional volume costs. It will also be helpful to highlight how countermeasures might be integrated into existing systems, for example, how meaningful complexity can be added into existing design through changes in lighting and use of varied materials, texture and color.

Finally, several SME's note that engineers tend to respond better to solutions than to problems, and that information on countermeasures can be best understood when it can be easily visualized, for example via a range of visual design examples with associated trade-offs.

Insert Countermeasures Early in the Planning Process

The mission planning and design process is a multi-phased effort that begins at the conceptual level and then moves through high level design, more detailed design (where habitable volume is set), development testing (including mock-ups), and finally the operational phase where the design is built and performance improvements are explored. Experts note that many countermeasures are not fully considered until the operational phase. The problem with that is that some countermeasures have design implications that need to be addressed at an earlier stage. For example, scientists may not have worked out the optimal viewing time and content of virtual windows, but considerations such as screen size, number, and placement have concrete design implications (e.g., outlet placement, rack design, stowage) that need to be incorporated early on in the design and tracked so that they are not lost as the design progresses.

4. Recommendations: Toward the Creation of a Countermeasure Portfolio for Long-Duration Spaceflight

INTRODUCTION

The risks to psychological and behavioral health inherent in the spaceflight environment are many, including:

- Sensory reduction and monotony
- Visual and auditory distractions
- Lack of control and autonomy
- Overscheduling/ overwork
- Boredom/ lack of intellectual stimulation
- Social isolation and monotony
- Lack of privacy
- Lack of opportunities for mental restoration and stress reduction

The goal of countermeasures is to reduce the negative psychological and behavioral effects of these environmental stressors either by improving the fit between crew and environment (by modifying the environment or by modifying the crew through selection and training) or by providing crew with strategies and mechanisms to cope with and recover from stressors.

Because of the extreme nature of spaceflight environments, there is no single countermeasure "silver bullet." Rather, we must think in terms of an integrated portfolio of countermeasures that addresses the range of environmental stressors and offers individual choice. Just as an investment portfolio is created to reduce overall financial risk by putting one's proverbial eggs in multiple baskets of different sizes and in different sectors, so would a countermeasure portfolio be used to reduce psychological and behavioral risk by including multiple countermeasures that address a range of different environmental risk factors at a range of scales. And just like a good investment portfolio, an effective countermeasure portfolio would continually evolve over time, with underperformers weeded out and promising new countermeasures added in, based on experience and new data.

This section lays out the content of a countermeasure portfolio, based on data from the extensive literature review of countermeasures and the operational assessment. In addition, research needs regarding specific countermeasures are discussed.

The Cost of Doing Nothing

Evidence from the broad literature review of environmental risk factors along with expert opinion from the operational assessment point to the many potential negative neurological, psychological and behavioral consequences of living and working in spaceflight environments. These effects range from relatively mild to very severe, and can include: mental fatigue, reduced productivity, impaired decision making, lapses in memory and attention, depression, sleep disturbances, interpersonal conflict and hostility, risk taking behavior, decreased resiliency to cope with stressors and crises, social withdrawal, and changes in neural structure.

Although we are aware of the potential for these severe consequences, limited spaceflight data and the idiosyncratic nature of each crew make it difficult to predict which problems will occur and which crew members will be most susceptible. The effects of long-duration missions are even harder to predict as there are even less data to go on. Despite this uncertainty, we can say with high confidence that crew members will experience significant stress, mental fatigue, and some neurophysiological changes and that these effects will tend to worsen over the course of a long-duration mission. The experts interviewed as part of the operational assessment were in agreement that failure to implement sufficient countermeasures to mitigate risks to psychological health would be disastrous, both for individual crew members and for mission success.

Because of the uncertainty related to the specific consequences of environmental stressors on a particular mission, the severity of these consequence, and the susceptibility of individual crew members, the approach to countermeasures should err on the side of over-planning and over-implementation, particularly for early missions. Flight psychologists talk about providing a large buffet of countermeasures that crew can select from and note that as we learn which countermeasures are the most useful, we can begin to fine-tune the buffet. As one psychologist put it, when it comes to incorporating countermeasures in capsule and mission design for long-duration flights, we have to "load the sucker up."

THE COUNTERMEASURE PORTFOLIO

The most promising countermeasures identified through the evidence review and the operational assessment are summarized in Table 1, along with an overview of the research and development needs regarding specific countermeasures. The order in which the countermeasures appear does not indicate relative importance as all are considered of high importance. Some countermeasures have significant associated research needs because we have little or no data on their effectiveness specifically in spaceflight and on the most effective and practical supporting technology. Other countermeasures have significant design needs but less significant up-front research needs (e.g., stowage system design). And still other countermeasures, although every bit as important, have less critical design and research needs because they have stood the test of time and have already been effectively implemented (e.g., the provision of digital entertainment such as movies, books, news, and sporting events).

Table 7. Recommended Countermeasures for Long-duration Spaceflight

	Countermeasure	Benefits	Research and Development Needs
Social Interaction and Support	Communication with ground (of various types)	Social connection and support	Continued development of technology and strategies for communicating in context of time delays
	Psych support	Help identify and solve psychological-related issues and problems	Evidence of benefits is already strong
	Virtual therapist	Provide psych support in cases of communication gaps/ no communication	Continued design and testing of expert/virtual systems
Group Cohesion and Positive Dynamics	Group recreation, games, activities	Team building; relieve social monotony	Evidence of benefits is strong; continued research on space appropriate games or use of commercial technology in space
	Communal eating	Team building; social interaction	Evidence of benefits is already strong
	Blogging/diary	Venting frustration; virtual social interaction; intellectual engagement	Evidence of benefits is already strong
	Celebrations (holidays/milestones)	Social interaction and team building; marking passage of time	Evidence of benefits is already strong
	Outlets for aggression (e.g., bull session, competitive games)	Can help stave off more serious problems with group functioning	Continued research and training on effective group strategies for conflict resolution
Views and Interaction with Nature, Virtual Nature, and Other Virtual Environments	Real windows	Mental restoration; stress reduction; connection with Earth/external environment	In context of LD spaceflight, research dollars probably better spent on virtual windows or on developing technology for integrating real and virtual windows
	Virtual windows	Mental restoration and stress reduction in context of everyday work/tasks; connection with Earth/home; sensory stimulation	Significant research needs – assessing benefits in high-fidelity analogues and in determining optimal content, size, placement, and technology
	Immersive virtual environments	Opportunity for deeper mental restoration and stress reduction; increase in resiliency; getting away; sensory stimulation	Significant research needs – assessing benefits in high-fidelity analogues and in determining optimal content, technology, placement, and immersion dose
	Plants/gardens	Mental restoration and stress reduction; sensory stimulation; psych benefits of caring for living thing	Appropriate technology exists; design development needed to optimize design and placement for psychological benefits; more research on psychological benefits in high-fidelity environments would be useful
	Green exercise	Mental restoration and stress reduction beyond that for exercise alone; increased motivation for/engagement in exercise	Technology development and testing for integrating virtual systems with exercise equipment
Capsule Design and Layout	Private quarters	Mental restoration and stress reduction; relief from social interactions; getting away	Significant research needs – determining minimum and optimal volume (or volume ranges) and design requirements
	Semi-private space	Quiet social engagement	Some research and design-test needs for determining required size and design (will depend in part on crew size)
	Communal space	Social engagement; team cohesion	Some research and design-test needs for determining required size and design (will depend in part on crew size)
	Comfortable and efficient work space	Reduces rate of mental fatigue and level of stress from work and environment sources; improved productivity	Some research and design-test needs for determining required size and design (will depend in part on crew size and mission requirements)
	Separation of spaces (physically and/or conceptually)	Assists with wayfinding/orientation; can create greater sense of space; reduces distraction	Design-test
	Flexible/ reconfigurable space	Increases sense of control; ability to change environment as needs change; personalization	Design-test

	Countermeasure	Benefits	Research and Development Needs
Interior Design	Increase meaningful sensory stimuli (visual, auditory, tactile, olfactory)	Helps ameliorate some of the negative impacts of a sensory-poor environment (e.g., neurophysiological changes and associated impacts on cognitive functioning) as well as provide a more humane place to live.	Design-test
	Organized and flexible stowage system and procedures	Reduces overall stress; helps protect against attention fatigue and its associated symptoms; improves efficiency and reduces frustration	Design-test
	Noise cancellation/ muffling	Reduces overall stress and demands on attention capacity	Anecdotal evidence suggests current noise levels/ noise reduction strategies on the ISS are acceptable
	Interface design to reduce information overload	Well-designed interfaces will reduce demands on attention (helping reduce mental fatigue) and improve work efficiency and monitoring capability	Technology development; need for design-test
	Adequate level and type of lighting	Helps reduce mental fatigue and improve performance. Lighting can also be used to improve mood, protect against SAD, and entrain sleep/wake cycles.	Additional research required on use of lighting to improve mood and influence sleep/wake cycles; design-test for lighting level and placement
Crew Selection and Management	Careful crew selection (individual traits and group compatibility)	Maximizes ability of crew to cope with long-duration spaceflight environmental stressors and to function as cohesive unit	Additional research needed on identifying optimal crew characteristics; modified procedures for selection that allow for crew input
	Extended training (including analogs)	Increased familiarity with stressors and improved coping skills for dealing with stressors	Additional planning and research needed to identify types of training required for LD missions and determine necessary length of analogue experience
	Sufficient meaningful work	Helps prevent boredom and associated negative symptoms and behaviors	address in mission planning and with input from crew
	Some crew autonomy	Intellectual engagement; feeling of control	Design into mission planning
	“Just in time” in-flight training	Reduces stress from trying to remember training; increases competency and ability to cope with the unexpected	Additional design and testing of effective methods and technologies for providing in-flight just-in-time training
Other	In-flight entertainment (movies, books, etc.)	Protection from boredom; connection with Earth; intellectual stimulation	Continued review of commercial technology and adaptability to in-flight entertainment
	Food variety and choice	Increased sensory stimulation; improved sense of control; overall well-being	Continued research on ways to increase food variety (and associated sensory stimuli) in LD spaceflight
	Meditation	Reduces stress and mental fatigue; increases psychological resiliency	Benefits of meditation have been well studied in military and other contexts; application in space environments should be straight-forward
	Pets	Social connection; benefits of caring for living thing; stress reduction	Research requirements in terms of determining space-appropriate pets (or virtual pets) and assessing benefits
	Sleep	Sleep already receives a great deal of attention in space research but it is worth pointing out that adequate sleep is one of the best countermeasures for restoring and maintain attentional functioning	Research is on-going
	Physical exercise	In addition to obvious benefits of maintaining muscle mass and bone density, exercise can help maintain brain health and improve mood	Research is on-going

SPECIFIC RESEARCH RECOMMENDATIONS

Several of the countermeasures listed in Table 1 have particularly high research needs, both because past research indicates that they will likely be important and effective in the spaceflight environment and because we do not currently know enough about how best to implement these countermeasures in spaceflight. The research needs regarding these countermeasures – specifically private space, virtual windows, and immersive virtual environments – are discussed in more detail below.

Private Space

Both past research and expert opinion indicate that private crew quarters will be a necessity rather than a luxury in long-duration spaceflight. There is less agreement, however, on how big private quarters need to be. In the absence of specific recommendations regarding volume, engineers are left without guidance and may, in fact, question the necessity of volume-intensive private space. Compounding the uncertainty regarding volume is the fact that optimal volume is highly dependent on design. A somewhat smaller volume space – if efficient, comfortable and otherwise well-designed – may well be preferable to a larger yet less well-designed space.

Given the large number of volume/design permutations, it is simply not possible to study and compare every alternative. It is, however, possible to explore and compare a smaller number of solutions that are grounded in research data, engineering constraints (e.g., in terms of launchable volume/mass and overall capsule shape), and best design practices. The notions of design charrettes and small experiments (discussed in the next section) are particularly relevant to research on private space. Below are some general research recommendations, based on the literature and operational reviews:

- Use the volume of current ISS private crew quarters (roughly 2 cubic meters) as a starting point for research and design and compare with options that are up to twice as large (and even slightly larger).

- Develop criteria for private quarter characteristics. Based on literature and operational reviews, these may include: space for comfortable sleep, space to don and doff clothing, work space, allowance for private communication with ground, adequate sound and vibration insulation, window or virtual window, allowance for engagement in virtual environments, storage for personal items, and ability to personalize space. This list could be further expanded and refined into essential characteristics and ideal characteristics based on input from current and former astronauts and from analogue crew, keeping in mind that the needs on a long-duration mission may be greater than those on a shorter duration mission.

- Develop a range of private quarter designs that span the different volumes discussed above and that meet, as much as possible, the criteria for quarter characteristics. The design process could be mediated by space architects and designers but should be a

collaborative effort between designers, engineers, crew members, human factors specialists, psychologists, and other stakeholders with relevant expertise.

- Test initial designs. In the early research stage, designs can be presented virtually or as rough models and need not necessarily be highly detailed. The goal should be to generate as much feedback as possible from astronauts and other experts before investing so much time and money into a few detailed mock-ups that it becomes difficult for designers and researchers to change course. Thus, initially research is used in an iterative fashion (a series of small experiments) to develop "best designs" for several different volumes along the range discussed above.

- Once initial research is completed and candidate designs have emerged, mock-ups can be constructed and higher fidelity research can be conducted. Research studies can assess and compare these quarters on outcomes such as: functionality; perceptions and attitudes of crew; and impacts on stress reduction, mental restoration, and other psychological and behavioral variables. Such research would help define design criteria, determine an acceptability threshold for private quarter volume, and pinpoint the additional benefits, if any, gained from larger volumes.

Virtual Windows

Both past research and expert opinion indicate that virtual windows are not only desired by crew members but that they can play an important role in stress reduction and attention restoration, providing micro-restorative opportunities throughout the day. Virtual windows also provide meaningful environmental stimuli, helping counteract some of the negative impacts of the low-stimulus spaceflight environment. In addition, the technology used for virtual windows (e.g., LED screens) can also be used for other purposes, such as communication, training, data display, and entertainment. In terms of using virtual windows for psychological well-being in the spaceflight environment, more research is needed to address the following questions:

- How large should virtual windows be? Past research indicates that larger images (e.g., the size of large screen TVs) have greater psychological benefits than smaller images (e.g., standard home desktop monitor size). Image size and placement, specifically the relationship of these variables to psychological and behavioral variables (e.g., stress level, mental fatigue levels, work efficiency, mood, and overall satisfaction with environment) should be further explored in the spaceflight environment.

- What is the most appropriate technology for virtual windows? Experts have pointed to possible problems in terms of launching and maintaining large screens. Alternatives may include flexible screens or a series of smaller screens that could be configured into larger sizes as needed and could be stowed when not needed (thus preserving surface real estate).

- What content should virtual scenes include? A wide range of studies in environmental psychology indicate that scenes that include elements eliciting "soft fascination" are particularly powerful in terms of maintaining and improving attentional capacity,

reducing overall stress, and improving mood. Nature scenes are particularly high in soft fascination and we would expect them to be as beneficial in spaceflight environments as they are in other contexts. Window content will also depend on the preferences of crew members and attention should be given to the range of scenes that might be desired and the relative impacts of these scenes. More information is also needed on whether static images (or a series of images) are sufficient, over the long term, to generate psychological benefits or whether images need to change, either over time (as the view through a real window would over the course of the day) or with the orientation of the viewer. Based on this research, guidelines could then be developed for window content.

Immersive Virtual Environments

Past research shows that immersive environments, specifically nature environments, can have powerful benefits in terms of stress reduction, recovery from mental fatigue, and giving a sometimes much needed sense of "being away." These environments also provide much needed brain stimulation, which may help to inhibit some of the neurophysiological changes reported in low stimuli environments. Virtual reality systems and other immersive systems can also be used for other important purposes, such as interactive training or interacting with a virtual therapist. In terms of using immersive environments for psychological well-being in spaceflight, more research is needed to address the following questions:

- Most of the studies showing psychological benefits from nature immersion have used either real nature settings or immersive settings created from projected images or video of real environments, often along with other sensory input such as nature sounds. Can the same benefits be realized from virtual environments based on computer simulations? The answer to this question has significant implications in terms of technology requirements for immersive environments.

- What is the best method and technology for creating immersive environments? Immersion can be achieved through virtual reality systems or through surround screens. With regard to virtual reality systems, are head-mounted systems feasible and desirable from an astronaut's point of view? Are they maintainable? Is there other virtual reality technology in existence or development (e.g., from the gaming community) that would be better? Is a lower technology solution (e.g., projected or displayed images on surround screens) preferable? How large do the screens need to be, where will they be mounted, and how would they be stored? How are other sensory inputs (e.g., sound, smell) best achieved? In regard to appropriate technology, a key factor to consider is sense of immersion as the greater the immersion, generally the larger the psychological benefits. Other important variables to consider are: comfort, usability, maintainability, and energy and storage requirements.

- What, specifically, are the psychological benefits of immersive environments for astronauts? In other words, do the benefits found for other populations translate?

- What is the best "dose" of immersion to maintain psychological well-being over the long run? Previous studies have shown that regular immersion over time is more

effective than infrequent or sporadic immersion. Several studies have shown positive benefits over time with a nature immersion dose of 3-4 times per week for roughly 30 minutes at a time. That is, perhaps, a good place to start for space or space analogue studies. However, although some of the populations in other studies were under consider considerable stress, they were not confined to isolated and extreme environments in the same way that astronauts are and the ideal dose for long-duration spaceflight may indeed be higher.

- What is the ideal content for immersive environments? Again, based on the many studies in environmental psychology, we can predict that immersive nature environments full of soft fascination (e.g., nature settings, fluttering leaves, winding trails, vistas, non-threatening animals, bird song) will have the greatest psychological benefits. Indeed, some of the content that may be desired by the user (such as those found in immersive video games) may in fact induce stress and fatigue. Although the use of virtual reality and immersive environments purely for entertainment purposes may be valid, the use of the systems specifically as a countermeasure to reduce environmental risk factors will need specific guidelines.

- How can immersive environments (e.g., nature trails) be integrated into exercise equipment? What benefits do these immersive environments confer upon crew members, beyond the benefits of exercise alone?

APPROACHES TO COUNTERMEASURE RESEARCH

As mentioned above, some of the countermeasures highlighted by the evidence review and operational assessment have so many different permutations and design possibilities that it is simply not possible to study them all in-depth. In these contexts, using a creative design process along with iterations of smaller experiments may be a useful way to develop a manageable set of good options that could then be more formally studied.

Design Charrettes

One way to jumpstart thinking about countermeasures, such as those related to capsule design, is to involve a wide range of stakeholders and generate a myriad of scenarios and potential design solutions through a design charrette. A charrette is a time-limited, multiparty, collaborative and structured event that is focused on attacking a complicated or multi-faceted problem and producing a range of potential solutions in a short amount of time (Lennertz, 2003; Lindsey et al., 2010). A charrette on capsule design, for example, could include engineers, space crew, mission control personnel, human factors experts, environmental psychologists, experts in space medicine, architects, interior designers, and others with specific skills or interests in space and other ICE environments. Charrettes are widely used in architecture, landscape architecture, urban planning, and community development. When done properly, they have the advantage of integrating the perspectives, ideas and interests of a diverse group of people in a climate that encourages creativity and thinking outside the box.

Small Experiments

Large research institutions and government agencies often have a bias toward large scale research. The benefits of many of these studies are undeniable, yet bigger is not always better. In the context of research regarding some of the countermeasures for mitigating psychological risk in spaceflight environments, a smaller scale approach – or more specifically, a series of smaller scale studies – may be more useful. Such a series of studies allows for incremental forward progress in the face of many unknowns and many possible research directions.

As R. Kaplan (1996) points out, small experiment is not synonymous with "quick and dirty" or "sloppy." Rather, "small" implies something of a relatively small scale, that doesn't try to do too much, doesn't require a huge sample size, and is relatively inexpensive. At the same time, "experiment" implies a search for an answer and, like any experiment, small experiments are not exempt from the requirements of good conceptualization, appropriate sampling, and meaningful assessment.

In the context of countermeasures research, the iterative use of small experiments and design charrettes would have a number of advantages:

- Provides a process whereby viable solutions can be teased out from the myriad of possibilities (i.e., by providing information in a timely and cost effective manner about what works and doesn't work and then plugging this information into the next experiment/iteration)

- Avoids early (and possible misdirected) commitment to a specific countermeasure design or implementation and thus can help avoid big mistakes

- Can result in more varied participation over time (both in terms of the people involved in the design process and in terms of the multiple small populations that can be tapped for iterative assessment)

- Provides defensible direction for a larger scale study (e.g., in identifying which high-fidelity crew quarter mock-ups to study or in identifying how best to create an immersive environment for a research study that addresses the question of dose).

COUNTERMEASURE INTEGRATION AND OVERSIGHT

An important theme emerged from interviews with experts during the operational assessment: Even if countermeasures are carefully identified, well researched, and widely accepted, this does not ensure that they will make it into capsule and mission designs or that mission scheduling will allow crew to make use of them.

If, as is argued here, the best strategy for mitigating environmental risks to psychological health is creating a *portfolio of countermeasures*, it follows that a *portfolio manager* is also required. Countermeasure development and integration will require consistent oversight, coordination, and advocacy at each stage of mission planning and development – from the initial development of mission requirements, to mission launch, and beyond.

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13. ABSTRACT *(Maximum 200 words)*

This study, based on extensive literature reviews and expert interviews, provides an in-depth look at the environmental stressors associated with long-duration spaceflight environments, outlines the risks that those stressors pose for psychological and behavioral health, and recommends a portfolio of countermeasures to help mitigate those risks. Section One provides a framework for understanding the environmental risk factors related to behavioral health and performance during long-duration spaceflight and details the observed consequences of those risks. This section is based on an extensive literature review across a broad range of fields. Section Two provides a review of the empirical evidence regarding specific countermeasures to reduce the risks associated with isolated, confined, and extreme environments. This section identifies which countermeasures may be particularly effective in reducing environmental stressors and maintaining psychological health and well-being in spaceflight environments. Section Three provides an operational assessment based on interviews with ten subject matter experts in fields relevant to psychological health in long-duration spaceflight. Results from this assessment offer additional insights regarding countermeasures. Section Four integrates lessons learned from the literature review, evidence review, and operational assessment to form specific recommendations for the development of a countermeasure portfolio. In addition, research needs regarding countermeasures are discussed.

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