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Human Adaptability for Deep Space Missions: An Exploratory Study

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Abstract

The present qualitative study conducts in-depth interviews with astronauts and other subject matter experts in order to shed light on human adaptability in extreme environments. Deep space travel will entail a range of highly stressful conditions to which astronauts must adapt. Feelings of isolation will be increased, as the space traveler is farther from Earth for longer periods of time. Daily life will take place in small and confined areas, for durations extending into years. The dangers of the extreme environment of space are ever-present, and failure of critical equipment or components can lead to death. Astronauts will need to function more autonomously, with diminished support from Earth. It is thus important to select and train future astronauts who are able to adapt to such extreme and variable conditions and continue to function effectively. Subject matter experts identify the central adaptive challenges faced by crewmembers, and what are the key individual attributes associated with human adaptability. Results also point to organizational factors, as well as several coping and resource strategies that can be applied to improve human adaptability to extreme environments and missions. These results can be used to inform selection and training programs, as well as the design of space vehicles, systems, and habitats in order to enhance astronaut adaptive task performance.

Keywords: adaptability, astronauts, extreme environments, stress, coping

In planning for future deep space missions, a major risk area identified by NASA concerns the ability of astronauts to adapt to the isolated, confined, and extreme (ICE) conditions that they will experience (NASA, 2019). It is known that people differ in how well and quickly they *adapt* to spaceflight and other ICE environments (Bartone, Krueger, & Bartone, 2018). However, the factors leading to such individual differences are not well understood. By developing this understanding, NASA and other organizations can improve the effectiveness of selection, training, and risk-mitigation strategies for future astronauts on long-duration missions.

NASA is actively planning for long-duration space exploration (LDSE) missions, with an anticipated crewed mission to Mars to take place in the early 2030s (NASA, 2014). All space missions entail unusual conditions to which astronauts must adapt, including isolation from family and friends, confinement in cramped, small spaces, and having to live and work in extreme environmental conditions where there is a constant risk of serious injury or death should some critical equipment

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fail. These demands are expected to increase greatly for astronauts on LDSE missions. According to NASA's 2019 Human Research Roadmap, in preparing deep space journey/habitation and planetary missions, "Given the extended duration of future missions and the isolated, confined and extreme environments, there is a possibility that (a) adverse cognitive or behavioral conditions will occur affecting crew health and performance; and (b) mental disorders could develop should adverse behavioral conditions be undetected and unmitigated" (NASA, 2019). Longer distances from Earth and coincident delays in communication will greatly increase the sense of isolation (NASA, 2019). Crews will have to function more autonomously, without ready advice or assistance from home base (NASA, 2015). At the same time, crew living spaces will be smaller, with more limited privacy (Drake, 2009; Whitmire et al., 2015). Exposure to environmental extremes such as heat, cold, and radiation will also be greater, and for longer time periods. Thus, it is critically important that astronauts on LDSE missions be able to adapt quickly and effectively to the range of ICE conditions that they are likely to encounter and problems that may suddenly arise. Indeed, adaptability is one of five critical competencies identified by NASA for astronauts on long-duration missions (Landon, Vessey, & Barrett, 2016).

Adaptability concerns the capacity of a person to change or adjust in response to changing conditions or situations (VandenBos, 2007). Recent years have seen an increase in studies of adaptability in work settings, in part due to the recognition that rapid technological advances are forcing workers and companies to change approaches more often in order to survive (Bell & Kozlowski, 2002; Burke, Pierce, & Salas, 2006). Studies have linked adaptability at work to a number of personal attributes, including intelligence (Bell & Kozlowski, 2008), emotional stability (Huang, Ryan, Zabel, & Palmer, 2014), conscientiousness (Griffin, Neal, & Parker, 2007), openness, extraversion (McLaughlin, Bowman, Bradley, & Mistlberger, 2008), self-awareness and tolerance for ambiguity (Gwinner, Bimer, Brown, & Kumar, 2005), hardiness (Bartone, Kelly, & Matthews, 2013), control (Wanberg & Banas, 2000), and mastery or achievement orientation (Chai, Zhao, & Babin, 2012; Pulakos, Arad, Donovan, & Plamandon, 2000). However, most of these studies were conducted with employees in conventional work environments. The capacity to adapt to ICE environments may require these and/or other attributes. A recent systematic review of studies addressing adaptability under ICE conditions confirmed the importance of intelligence, emotional stability, openness, mastery, and hardiness (Bartone et al., 2018). This study found that past experience, active coping style, and a moderate level of introversion also facilitated adaptability under extreme conditions.

Through interviews with former astronauts and other experts, the present study seeks to shed further light on factors linked to adaptability to ICE environments, and also to identify effective strategies for coping and maximizing adaptive capacity. We address four key questions: (1) What are the key sources of stress for people engaged in long-term missions in extreme environments? (2) What individual factors influence adaptability? (3) What social and organizational factors influence adaptability? (4) What coping strategies are effective in maintaining adaptive performance under extreme conditions? Figure 1 presents a model showing the hypothesized relations among these factors. In this model, tasks as performed by astronauts are represented as the relevant outcome of interest, in this case adaptive task performance.

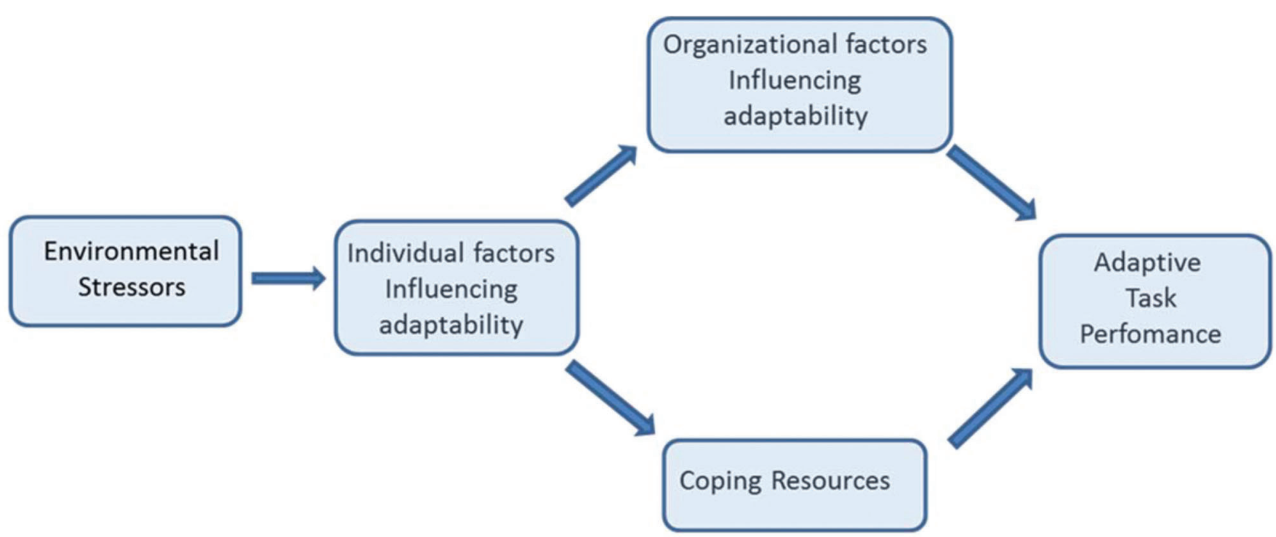

Figure 1. Model showing presumed relations among factors influencing adaptability to ICE environments. In this framework, organizational factors and coping resources serve to mediate the impact of stress on adaptive task performance.

Methods

Subjects

The study was commissioned by NASA, and NASA provided the participants and set the format for interviews. Eight subject matter experts (SMEs) from NASA were interviewed, and one additional expert (polar explorer) was identified by the authors and approved by NASA. Due to constraints on the time and availability of astronauts as stipulated by the NASA Astronaut Office, no female astronauts were available to participate in this research. All research participants were thus male, with an age range of 38–64 years. All had extensive experience with human operations in ICE environments. Subjects included three experienced astronauts, a senior psychologist at NASA, two NASA operational psychologists, a NASA scientist engineer with extensive Antarctic experience, a NASA flight surgeon, and a polar explorer who has traversed both poles. Years of experience in space or analogous environments ranged from 15 to 40 years.

Procedure

Interviews were conducted by telephone conference calls of between 60 and 90 minutes. Following a brief introduction by the NASA Behavioral Health and Performance project manager, one investigator conducted the interview while two to four others took detailed notes. Following each interview, all notes were aggregated into a single document reflecting the master record for that interview.

The interview format was semi-structured, following an interview guide developed by the authors to address questions about individual differences in human adaptability to ICE environments. After asking the interviewee to describe his background and experience, our questions covered four main categories: (1) challenges or stressors in long-term missions in extreme environments; (2) individual factors that influence adaptability; (3) social and organizational factors that influence adaptability; and (4) coping strategies and resources that help maintain adaptability under extreme conditions.

Analysis

Following grounded theory procedures for qualitative analysis as recommended by Charmaz (2006; 2012) and Castleberry & Nolen (2018), a thematic analysis was performed on the interviews in order to identify the unique and recurrent issues within each of the content areas. In the first stage of analysis, a coding scheme was developed that reflected factors from the scientific literature previously found to be related to human adaptability in extreme environments (Bartone, Adler, & Vaitkus, 1998; Bartone et al., 2018). In the case of stressors for example, these included isolation, danger, uncertainty, powerlessness, and boredom. Any novel issues or themes mentioned by the interviewees were also noted. Novel stressors that emerged for example included "confined space for living and working" and "communication delays and problems." These themes are listed in Tables 1–4.

In the next stage of analysis, interview records were re-examined to identify whether or not a given theme was mentioned by the SME being interviewed. Two independent raters coded the theme. If an issue or theme was mentioned in the interview, the passage was marked and the theme code was scored positively for that interview. Agreement across raters was high, and ranged from 85% to 97% across the categories. Discrepancies were resolved through discussion. Results are presented in sequence for the four major topical areas covered in the interview.

Results

Stress Factors

Table 1 summarizes the factors identified by SMEs that represent the major stressors and challenges encountered in the ICE environment of long-duration space missions. The ten most commonly mentioned issues are detailed further below.

Isolation

The sense of isolation was the most commonly mentioned challenge to face humans on long-duration space flight and analogous ICE missions. On deep space missions such as to Mars, astronauts will be more distant and disconnected from Earth. Experts spoke about the loss of social support that is normally provided by friends and families. Even though they will have other crewmembers around, that is not the same as having one's own family and

Table 1
Sources of stress in ICE environments, and number of SMEs mentioning.

Theme	Number of SMEs
• Isolation	7
• Physical dangers/discomforts	6
• Work pressures/pressure to perform/time pressure	6
• Worried about family/missing family	6
• Lack of privacy	5
• Interpersonal relations	5
• Confined space for living and working	4
• Communication delays and problems	4
• Uncertainty/unpredictability	4
• Equipment reliability problems	4
• Reality not matched by expectations	4
• Micromanaging by ground controllers	3
• Physical demands of extreme environment	2
• Sleep disruption	2
• Monotony/boredom	1

Note. Based on interviews with nine SMEs.

social network available. Although "you are with other people, they are not *your* people."

Physical dangers/discomforts

Physical danger was described as a near-constant source of stress. Space is a hostile environment for humans, and the physical risks are ever-present. Dangers that were mentioned include radiation, the ill-effects of microgravity on the body (e.g., bone and muscle loss), and having adequate oxygenated air to breathe. Astronauts are also fully dependent for water and food on whatever on-board supplies and technologies are available. Equipment failures or misjudgments can lead to fatal consequences. In addition, interviewees spoke about the physical discomforts associated with long-duration exploration missions. Astronauts are frequently exposed to extremes of heat and cold, noise, and cluttered, cramped living and working conditions.[1] Simple things like eating, sleeping, and defecating can be difficult and tedious. Unpleasant and persistent noise and odors often cannot be avoided.

Work pressures/pressure to perform/time pressure

Work pressure was also frequently mentioned as a stressor. Here, interviewees discussed the nearly constant demands of performing tasks on a strict schedule, and with extensive oversight from NASA ground control. Astronauts were said to work in "a fish bowl" with "lots of telemetry." There is a perception that NASA ground control is always watching, always evaluating what the astronauts are doing. Paraphrasing one expert, "There's great pressure to perform, and everyone is watching. You don't want to screw up for the whole world to see." For long-duration exploration missions such as to Mars, interviewees anticipated there will be less immediate oversight from NASA and ground control due to the long distances and communications delays. However, the pressure to perform will still be present for these crews. Experts also indicated that workplace stress is compounded on long-duration missions due to the confined quarters and lack of privacy from other crewmembers.

Worries about family/missing family

This overlapped with isolation discussed above. The main concern expressed here was that astronauts would be concerned about the safety and welfare of their families while they were gone for extended periods of time.

Lack of privacy

Experts mentioned lack of privacy as a stressor on long-duration missions. This overlaps with confined living space and is discussed below.

Interpersonal relations

Interviewees identified multiple social and interpersonal relationship challenges for long-duration mission crews. The demands of adjusting to and getting along with fellow crewmembers for extended periods of time were identified as substantial. Experts described the emotional stress of accommodating to crewmates as highest during the initial period of the mission. Part of this adjustment is getting to know the professional skills and capabilities of one's fellows, and how they will perform under pressure in the reality of an actual space mission. This is true despite time spent in preflight training together on the ground and in simulated conditions. Also people are different, with quirks and idiosyncrasies that others may find annoying. This will likely be further complicated by cultural and sex differences that will be present in international and mixed-gender crews. Leadership was deemed to be critically important in this regard as well. Leaders or mission commanders may be reluctant to let other crewmembers take the lead in areas where they have greater expertise. All crewmembers face the challenge of balancing roles and demands, both on the mission and with respect to family roles at home. Experts also discussed the problem that sometimes emerges in astronaut crews of members competing for more prestigious or high-visibility jobs during the mission. To quote another SME:

> Some tasks are definitely seen as more prestigious than others, as a result of visibility or perceived risk. For example, EVAs (extra-vehicular activities) or robotics operations are more desirable, as is being part of the flight deck as opposed to a non-active member of a mission. And this can cause crew friction.

Managing these interpersonal issues will be more important as mission length increases.

Confined space for living and working

The extended time that long-duration crews must spend in small, confined spaces was noted in the interviews as a major challenge and stressor. On a Mars mission, both outbound and inbound traverses will place crews in capsules with limited space for projected 6–8 months at a time. Compared to the International Space Station, the transit space vehicle will have a much smaller area of habitable volume and a higher density of people (Kanas & Manzey, 2008; NASA, 2019). The period on Mars should provide a less cramped habitat and somewhat more freedom of movement, but the sense of confinement will still be profound. In these highly confined conditions, the lack of privacy is expected to be a further source of stress for most astronauts. Interviewees described the constant "in your face" presence of other crewmembers as an increased challenge, highlighting the need for some kind of visual privacy. The concern for privacy also extends

[1] These environmental risk factors are detailed in the NASA Human Research Roadmap (NASA, 2019).

to mission control. One expert held that the constant monitoring by NASA ground control and lack of any personal or private space for astronauts could lead to diminished morale and performance.

Communication delays and problems

Interviewees reported that long delays in communications between deep space astronaut locations and Earth will pose a significant source of stress for crews. For a mission to Mars, radio communications are expected to be delayed by 10 to 20 minutes (Holland, Vessey, & Barrett, 2014). Communications with home will be sporadic and asynchronous, with no opportunity to respond immediately or get clarification, increasing the sense of isolation and leading to heightened sensitivities and potential misunderstandings (Kanas & Manzey, 2008; Landon, Rokholt, Slack, & Pecena, 2016). Reliable communications systems and schedules will help, but unanticipated problems and issues will likely arise leading to crew stress. These delays may contribute to the sense of crew isolation.

Uncertainty/unpredictability

Many of the SME comments focused on the uncertainty and unpredictability encountered on space missions. The uncertainty is mainly about the extreme environment that surrounds crewmembers, not knowing what is there and what may be coming next. This is also the case in extreme space-analogous environments, such as Antarctica. Storms can arise suddenly and without warning, the atmosphere can change, equipment can malfunction. Another major source of uncertainty concerns one's own health and capabilities. As one interviewee said, "There's also uncertainty about yourself. You might have some health problem come up, for example a problem with your knees. You get worried about medical things, body pains. Health problems can cripple you, stop you." Uncertainty exists also regarding fellow crewmembers, as one can never be sure how they will react over time and in different situations.

Equipment reliability problems

Related to the unpredictability of the environment, there is a need for *high* reliability in both equipment and people. Comments focused on the need for equipment and systems that could be relied on to perform and not break down, and for critical systems to be designed so as to permit easy access for maintenance and repair. Crewmembers for these missions need to possess a high level of technical expertise, including the ability to diagnose equipment problems, and to break down and assemble hardware components. To paraphrase one SME: "There's a need for cross-training and adaptability to trouble shoot hardware problems, and for example if the primary physician goes down, the rest of the crew will need to adapt to that." It is thus important to staff long-duration missions with astronauts and mission specialists who possess broad experience and technical competence in multiple areas.

Factors mentioned less often, but still deemed important by several experts include micromanaging by leaders and ground controllers, unrealistic expectations not matched by reality, physical demands, disrupted sleep, and boredom or monotony.

Individual Factors

The next category explored individual factors associated with adaptability. Table 2 summarizes the factors identified and the number of interviewees who mentioned them. In what follows these are discussed along with some illustrative quotes from the interviews.

Mental flexibility was frequently mentioned as a quality contributing to adaptability. All of the interviewees believed it was important to have a mindset that was open to change and adjustment depending on the situation. For some, flexibility was linked to *openness* as well as *humility*, understanding that one's own solution is not always the best solution. *Lack of flexibility* was uniformly seen as detracting from adaptability. Quoting one interviewee: "My commander had a reputation, and all during training and to the end of the mission he was inflexible, hard headed, wanted his own way." Another subject described most early astronauts, who were drawn from the test pilot community, as largely inflexible, and not suited for new

Table 2
Individual factors linked to adaptability, and number of SMEs mentioning.

Theme	Number of SMEs
• Mental flexibility	9
• Awareness of self and others	9
• Previous experience	8
• Technical expertise/skills	7
• Control/self-control	7
• Humility	7
• Emotional awareness/emotional control	6
• Commitment/passion/engagement	5
• Openness	5
• Sense of challenge/willing to try new things	5
• Team orientation	5
• Broad sense of perspective	5
• Motivated to learn/learn from failures and move on	5
• Cultural awareness/respect for differences	4
• Confidence	4
• Optimism	4
• Calm under pressure	4
• Physically fit/stamina	3
• Creativity/creative problem solving	3
• Practical intelligence/tinkerer/likes to build and fix things	3
• Curiosity	3
• Hardiness	2
• Discipline	2
• Patience	1
• Humor	1

Note. Based on interviews with nine SMEs.

kinds of deep space missions: "Earlier, most astronauts were military test pilots. There's a certain rigidity there. A lot of them would not have made good long duration crewmembers. They don't have that 'get along' mentality." Also, while a sense of *control* was generally seen as valuable and adaptive, too strong a sense of control could also lead to inflexibility.

Awareness of self and others was likewise often mentioned as important for adaptability. This entails an honest awareness of one's own emotions and capabilities, and a readiness to change, as seen in this comment:

> They (astronauts) also need to be honest with themselves, to maintain a high degree of self-awareness. They are honest in recognizing what they need to change in themselves; in what they need to "fix" about themselves. They take initiative to fix themselves. They are very open-minded to their own needs to change; and they are enthusiastic to seek out ways to get better.

Another interviewee also spoke about the importance of *being aware of one's own and others' limitations*. For example, he described his experience on the Space Station:

> Realistic social adaptability is a big part of adaptability. If you misjudge it, you can die. We had a Russian cosmonaut who was having mental and medical problems, such as cardiac arrhythmia and confused decision making, but he did not want to quit. That's not hardiness, that's hubris. This happens when there's a lack of self-awareness, and poor preparation. He had to eventually be medically evacuated from the mission.

Awareness of others was also seen as important for crew adaptability. On long-duration exploration missions, it will be important for crewmembers to show *mutual respect* and understanding. As one SME maintained: "It's most important to have respect for one another. Respect for what the others bring. There is a hierarchy in space, based on experience, rank, etc. It creates a bit of tension, but this won't matter so much on LDSE missions. Maintaining respect even with a hierarchy is important." Some interviewees discussed this further in the context of cultural awareness, as when crews are diverse in terms of nationality, gender, or race.

Previous experience was identified as another important factor influencing adaptability. People with more broad and varied experience, who have had to adjust and adapt in the past, are more adaptable. Past experience provides *confidence* that one can adapt to novel situations. Related to this, being able to take a broad or strategic perspective, "seeing the big picture," is important, especially in confined group living conditions where "small things can easily escalate into a big deal, can get really big. You have to keep things in perspective." In a similar vein, the "ability to self-regulate" and maintain *control over one's emotions* and reactions were identified as important factors for adaptability. Some SMEs described this in terms of *discipline*, or the ability to maintain control and stay task-focused under pressure.

Technical knowledge and skills were also identified as necessary for adaptability on long-duration missions. High levels of professional expertise and competence directly contribute to adaptability, and are also indirectly beneficial by helping to build mutual trust within the crew. Several other factors were mentioned. In addition to technical skill, one needs to have passion, the *motivation to learn* and develop new skills. The ability to observe carefully, flexibility, and *curiosity* were also mentioned. Related to curiosity, experts noted the *desire to learn*, *openness* to new ideas, willingness to take risks, and "being willing to try new things that others may not be willing to try." Several interviewees indicated that being a "tinkerer" is important, someone who "enjoys taking things apart and putting them back together again."

Several experts discussed the importance of having a *team orientation*, with a keen awareness of self and others. In long-duration team missions, it is important to be able to place one's own individual goals and desires secondary to those of the team, a kind of *humility*. This may be an especially significant factor for leaders. According to one interviewee:

> I like to say you need ego strength without ego-centrism. My commander was outstanding; one of the best flyers in the business. His success is the success of the crew. Very unusual for a [nationality], who tend to be blame-centric. Keeping strong without having to be in the spotlight all the time is huge.

As previously mentioned, *control* was regarded as important, although it can also be a "two-edged sword." The sense of control positively influences careful preplanning, training, and preparation, and adds to confidence that one can cope with surprise situations. On the other hand, control can be overdone, as with people who try to exert too much control. Quoting one expert: "With astronauts we have a population that loves control, they scan, forecast, plan, control threats. This saves energy and mitigates having to adapt. But there are some who are too rigid, and try to control everything. Control becomes a double-edged sword for them."

So control is valuable for adaptability, but needs to be balanced with openness and flexibility. Related to this is *optimism*, having the belief and confidence that one can adapt and recover from any situation that may come up, and that "no situation is un-winnable."

For exploration missions in particular, experts saw *interpersonal and cultural awareness* and sensitivity as important factors contributing to adaptability, recognizing that these crews will likely be multinational and of mixed gender. Since they will be confined together for up to three years or more, it is essential to have crewmembers who will respect and cooperate with each other. In this regard, one interviewee discussed the value of "learning the language" of one's crewmates (paraphrasing): "You've got to learn to speak the language of your crewmates. These are not just assets, but requirements. Make an attempt to know the culture and traditions of others. You find out you have more in common than you would initially think. It shows respect."

Physical fitness and stamina as well as the ability to remain *calm under pressure* were seen as important for adaptability. If an astronaut cannot accomplish the necessary physical tasks and cope with environmental extremes, then everything suffers. This is also related to coping with workplace stress, which includes constant exposure to uncomfortable and cramped conditions. Other stressful features of the space environment include demanding time schedules, technically challenging tasks, pressure to succeed, and the constant presence of crewmates. One interviewee indicated that coping with stress should be part of the astronaut selection process:

> Individual backgrounds will tell you how individuals handle stress in the workplace. I think there are some individuals who like to be in a stressful workplace. I don't think the [military service] made me want to do those [stressful] things. I went into the military because I'm attracted to those things. People need to be attracted to a stressful workplace before they even apply for a job like this. It should be part of the selection process.

This highlights the value of identifying astronaut candidates who tend to see stressful conditions as challenging and interesting, sometimes referred to as hardiness (Bartone et al., 2013).

An additional adaptability quality emphasized by our experts was *creative problem solving*. This was viewed as particularly important in a professional culture where there is so much preplanning and preparation, where so much of what astronauts do is guided by standard procedures and checklists. In this environment, it may be especially difficult to forego the standard ways of doing things and create novel solutions to address unanticipated problems. The following quote exemplifies this issue:

> Let me tell you why creative problem solving is so important. We have checklists for everything on the space station, for flying, performing experiments. The problem with checklists is we created them because we already know the problem, and we know how to behave. In an emergency you just have to find the right checklist, and the rest is done for you. The real emergency is the one you didn't expect at all, which you don't have a checklist for. That's when creative problem solving becomes fundamental, because we will run into those kinds of problems. On a mission to Mars, those individuals will have to be capable of adapting something that exists to make do for something that doesn't exist. And that's true for every step of the trip.

Creative problem solving and the ability to innovate are widely recognized as valuable adaptability qualities in many occupations. But it may be even more important in long-duration missions, where novel situations will certainly be encountered, and available resources—including advice from the ground—will be limited.

Social and Organizational Factors

The next category addressed social and organizational factors that may influence individual adaptability. Results are summarized in Table 3.

Support from the home organization or mission control was a key issue identified here. Embedded in these responses is a concern about control and autonomy; astronauts and operators wish to have greater control over their daily schedules and activities. Adaptability can be stifled when the home organization imposes excessive or unnecessary restrictions on the operators' schedules and activities. Also, good communication within the crew was seen as important, as well as mechanisms for safely discharging small interpersonal tensions before they can become major problems.

Connections with home—family and community—were thought to be important for maintaining adaptability throughout the course of the mission. Our experts spoke about the greater difficulties that long-duration crews can expect to have in keeping up contact with Earth, due to the great distances and communications delays. In this context, *good communications systems* are essential. Support from ground control is expected to be important for finding ways to keep astronauts informed and connected. At the same time, both astronauts and ground control operators must

Table 3
Social and organizational factors linked to adaptability, and number of SMEs mentioning.

Theme	Number of SMEs
Support from mission control/home base	8
Good communications and systems	7
Group cohesiveness and teamwork	7
Social support from family and friends	6
Trust (e.g., between crew and ground control)	4
Mental health support/safe place to vent	3
Group meals	1
Variety in food	1

Note. Based on interviews with nine SMEs.

accept that long-duration crews will be more autonomous, and train accordingly.

A frequent theme in this part of the interview concerned the tendency for the home organization—NASA or ground control—to micromanage space operations, and not give full consideration to the astronauts' situation. Interviewees described ground controllers sometimes issuing requests or directives without awareness of the realities being experienced in the deployed environment. As one expert said: "If the home organization is not in the proper mindset of what the deployed group is going through, there is a disconnect that can damage adaptability and performance. If they (ground controllers) tell you to do something that doesn't make sense, just to check a box to look good, this can affect morale and lead to problems." Placing former astronauts in ground control positions is seen as helpful, but even those who have "been there before" can forget what it is like and make unreasonable demands. The experts indicated that ground control personnel should train as much as possible with the astronaut crews they will be supporting on long-duration missions, in order to build *mutual respect and trust* before the mission unfolds. It was also recommended that stability be maintained in ground support personnel throughout a given mission, as opposed to frequent rotation of personnel.

In discussing organizational factors that can influence adaptability, one interviewee described the *mental health support* and benefits derived from a periodic "team assessment survey" provided to his crew in training. This was an anonymous survey meant to identify interpersonal and social issues that crewmembers may be experiencing, and provide a "safe" way to vent or discuss and resolve them as a group. The interviewee indicated this intervention was particularly helpful in facilitating continued social adaptation among his crew: "Something that helped us, our team would take a periodic anonymous team assessment survey, and then the four of us would talk with each other about the results. Talk it over and communicate about it. It was a way to safely blow off steam, take the edge off things that were irritating, and get the conversation started." Techniques such as this may be especially useful for minimizing interpersonal tensions during long-duration missions.

Experts indicated that *social support* from family and friends, as well as ground control, was important, and recommended that the organization design systems and procedures to facilitate. For example, there should be time allowed in the schedule to read or write letters to home, emails, videos, etc., and the onboard systems and technologies to support such communications. Interviewees also noted the importance of planners building variety into their daily food rations, and designing space vehicles that include areas for group meals and other team activities. This was believed to help maintain crew adaptability, cohesion, and teamwork.

Table 4
Coping resources for maintaining adaptability, and number of SMEs mentioning.

Theme	Number of SMEs
Careful planning/preparation/training	9
Connections with family and home/good communications	5
Have realistic expectations	5
Exercise/physical fitness	4
Engage in hobbies (e.g., photography, music)	4
Maintain some privacy	2
Keep a diary	2
Compartmentalize (e.g., focus on tasks not emotions)	2
Fairness, equity in task assignments	2
Imagination/positive thoughts	2
Pursue short-term goals	1
Maintain routines	1

Note. Based on interviews with nine SMEs.

Coping Resources

The final category addressed coping strategies, or techniques used to maintain one's capacity to adapt to the challenges of ICE environments. Responses, summarized in Table 4, are further discussed below with some illustrative quotes from the interviews.

Careful planning and preparation was mentioned by all the interviewees as an important factor for maintaining adaptability over the course of a mission: the better prepared one is, the better able one is to adjust and respond to a variety of conditions. This includes planning ahead before the mission begins, as well as ongoing training and preparation while the mission is underway. Maintaining *regular contact with home and family* was frequently mentioned as important for coping and maintaining adaptability. *Communications with home*, including regular news feeds, is expected to reduce feelings of isolation in particular. Obviously this will be more challenging on long-duration missions such as to Mars. Even if communications are irregular and asynchronous, it is important to maintain these contacts. Related to this, it is also beneficial to establish *realistic expectations* with crews prior to the mission, and not promising astronauts benefits or capabilities during the mission that may be difficult or impossible to deliver. One SME described the value of realistic expectations with regard to communications capabilities while in space, as follows:

> Communication with family is important on long duration missions. Before we had all this communications capability, we would get email just once a day, in the evening. That was the way it was. Then continuous synching came along and we could get and read emails from home throughout the day, whenever we had time. That's great, but before was fine too, because there were no other expectations. As long as understanding and expectations are clear, everything is OK.

Regarding family support, SMEs discussed the value of having one's family engaged in various ways on the mission. For example, family members have helped in posting regular updates and photographs from space to personal websites. Involving families in training activities, and providing mission-related activities for them to do can greatly increase their understanding and commitment to the mission, which in turn may enhance an astronaut's ability to maintain adaptability.

Experts further highlighted the importance of *maintaining physical fitness* throughout a mission, in order to be able to react and respond to novel, demanding challenges that may come up, as well as routine tasks. Exercise can also be a good way of "blowing off steam." Having *personal interests or hobbies* that one can pursue during periods of low activity or recovery was seen as a valuable coping resource. This will vary for different people, but may include photography, writing, reading, listening to or creating music, creating recipes, or learning a new language. By and large, those we interviewed did not think that boredom would be a major problem on long-duration missions, as long as astronauts are selected who are comfortable being on their own and have a natural curiosity and interest in things. These people will always find interesting and engaging things to do. According to one: "I'm not worried about boredom on a long (space) trip. There are so many things you can do! You can tinker and make things better, you don't have to wait for things to break. Maintaining yourself, the ship, training in flight, science experiments, improving the ship, hobbies and different things you can do in the weightless environment."

Being able to have some *private time* away from other crewmembers was regarded as an important coping resource, as was privacy in general. As one SME described this factor:

> One day you may have 6 people on the flight. Five of them may be having dinner, and the sixth one may be just off on his or her own. There has to be the understanding that this is perfectly fine. Respect your private world, your inner world, when you need to. Don't feel obligated to always be part of the team. And at the same time, be as much a part of the team as you can. Because the team will need you, but not to the degree of creating personal problems within yourself. You need to be happy in order to function well with the rest of the crew.

There are design considerations here as well. Despite the limited habitable spaces available, designers should provide structures that afford crewmembers some private areas.

Several interviewees spoke of the tendency for astronauts to "*compartmentalize*" as a short-term coping strategy, taking stressors or negative emotions and "tucking them away" in order to focus on task accomplishment and crew cooperation. But at the same time "compartmentalization has limits…you can do it for only so long." *Keeping a diary* and/or writing letters can provide a safe means for expressing thoughts and feelings that one may wish to keep private. According to one SME:

> I kept a diary. This is very useful. You can let off pressure and say things in the diary that you don't want to say out loud to your teammates. The diary is one of the best, most important things out there. You shouldn't say all your thoughts to a colleague. With the diary you can let off pressure, get your worries out. Also you can dream a bit in your diary. Making a good shopping list, recipes, you can use your brain in a diary. The missions are so much routine and monotony—with the diary lots of feelings can get out.

Another important point raised in this category concerns *fairness*, or the equitable distribution of tasks and responsibilities on board. As mentioned earlier, some tasks are inherently more exciting and desirable, such as EVAs and robotics operations, while others are more mundane yet still essential, such as fixing a clogged toilet. Depending on their specialty areas and training, astronauts may well have different preferences as to what mission tasks they would most want to do. One interviewee suggested that mission planners should find out from astronauts in advance of long-duration missions what their goals and expectations are, and strive to assign them tasks that will be most meaningful for them:

> It would be great for astronauts to be more aware of what they want to get out of the mission, and see if that can be arranged. We should ask them. Transit to Mars is going to be a hard, long time. When you get to Mars, make sure everybody gets the chance to do something that's important to them. There should be a way to distribute the tasks so that everyone can be excited about getting to Mars.

Other coping strategies mentioned included using imagination to *maintain positive thoughts*, pursuing *short-term goals*, and following *regular routines*. It is valuable to establish routines that provide some regularity and predictability to daily life. This can include, for example, having regular times for meals and exercise.

Discussion

This study provides insights into sources of stress, and the factors contributing to adaptability of astronauts, and others who must cope with long periods in ICE environments. Results indicate major stress challenges for future astronauts will include isolation, physical danger, work pressures, long communication delays, family concerns, interpersonal relations, and lack of privacy. This largely corresponds with what others have reported, as for example in an Arctic Mars simulation (Bishop, Kobrick, Battler, & Binsted (2010), and in studies of polar explorers (Stuster, Bachelard, & Suedfeld, 2000).

At the individual level, important adaptability factors include self-awareness, control (both self-control and the generalized expectation that one can influence outcomes), social awareness and the ability to get along with others (team-player, non-defensive), the ability to change roles when necessary, commitment, personal competence or self-efficacy, and a sense of challenge and willingness to try new things. Additionally, subject matter experts emphasized the ability to stay calm under stress and to remain focused in high-pressure situations, which is related to self-control and emotional control. These findings align with previous studies showing that personality hardiness, which includes a sense of commitment, control, and challenge, predicts adaptability under a variety of extreme conditions (Eid, Johnsen, Saus, & Risberg, 2004; Johnsen et al., 2013). Past experiences with situations requiring change are also valuable for developing adaptability. This is in line with research demonstrating the importance of previous successful adaptation experiences (Burke & Orlick, 2003).

Individual factors identified by SMEs in the present study as contributing to astronaut adaptability for long-duration missions correspond well with astronaut competencies needed for long-duration missions, as identified by NASA investigators. Through a series of job analysis studies, NASA identified critical astronaut competencies for missions of various lengths (Barrett, Holland, & Vessey, 2015; Holland et al., 2014). For long-duration missions (defined as 12–36 months), seven competencies were identified as most important for consideration in both selection and training of astronauts: self-care and self-regulation; technical expertise; small-group living; operational problem solving; motivation; teamwork; and adaptability.

Figure 2 shows these competencies mapped against the individual adaptability factors identified in the present study. For example, contributing to the self-care, self-regulation competency are self-control, emotional awareness, and physical fitness. While many of the factors we identified may relate to more than one astronaut

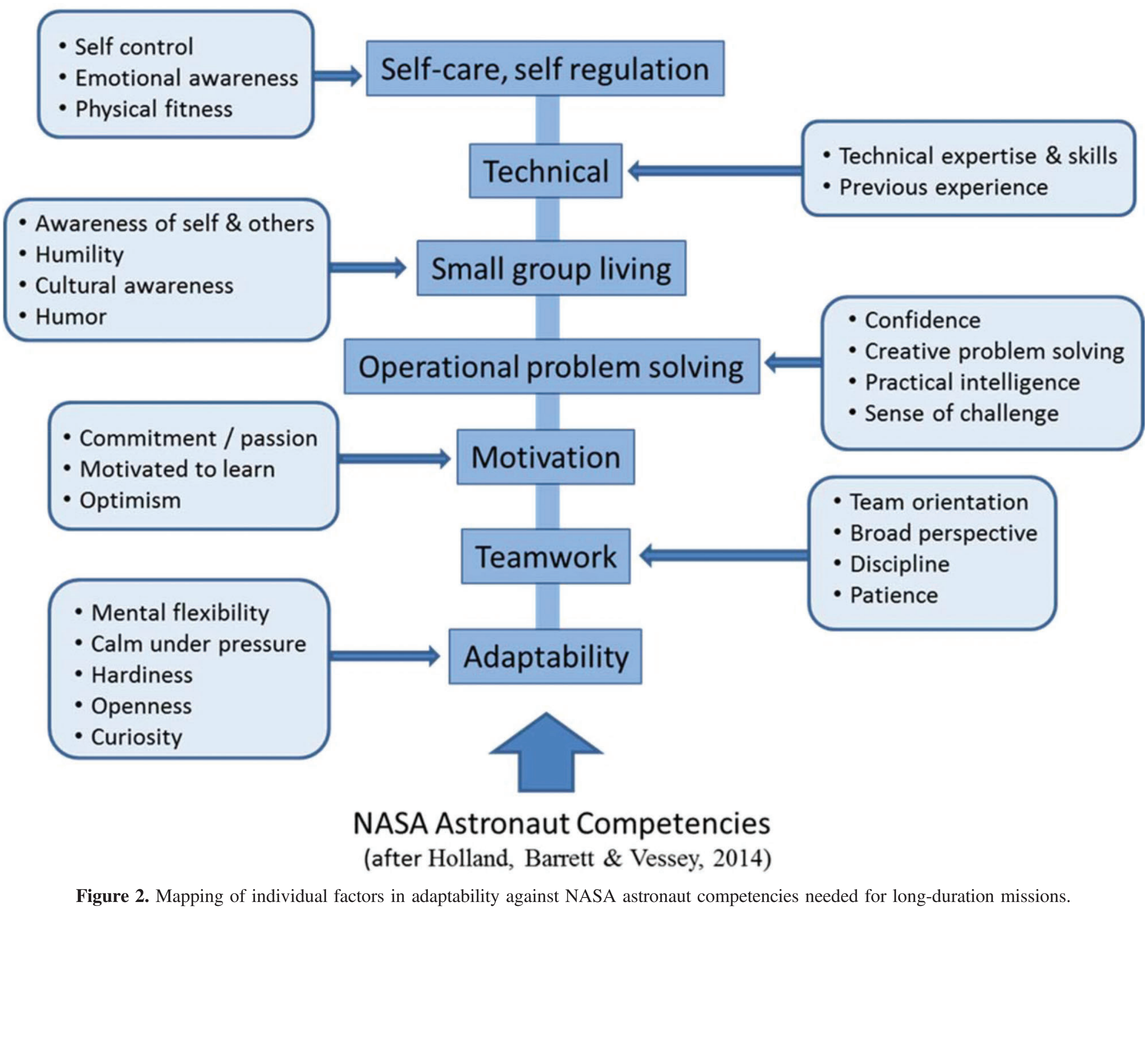

Figure 2. Mapping of individual factors in adaptability against NASA astronaut competencies needed for long-duration missions.

competency, the figure displays only the most direct links of factors with astronaut competencies. For example, the individual adaptability factor of creative problem solving relates most directly to the astronaut competency of operational problem solving. However, it is also related to the astronaut competency of adaptability.

Social and organizational factors that can impact individual adaptability in ICE conditions include "connectedness" with Earth, home, and family, cohesion and support from coworkers and ground control, social support from family and friends, and mental health support. On long-duration space missions, the sense of isolation from Earth and home will be extreme (NASA, 2019), and needs to be countered with a high level of perceived support and connection with those back on Earth. Long communication delays will also make it more important to maintain open and trusting relations with controllers on the ground (Kanas & Manzey, 2008). At the same time, the ongoing support and social awareness from one's crewmates becomes more important for maintaining adaptability over the course of long-duration missions. Interpersonal tensions during the initial and later stages of a mission can also be mitigated to some degree by providing crews with ample time and opportunities to train and even live together on the ground prior to actual operations.

This study also revealed several important coping strategies that may facilitate continued adaptability for humans engaged in ICE missions. Careful planning and preparation helps avoid problems, and builds confidence and reassurance that the mission will succeed. This is what Griffin & Hesketh (2003) refer to as *proactive adaptability*. Related to this, developing and honing the technical skills and knowledge needed for the mission also build confidence.

Other coping strategies include the use of positive mental imagery and imagination, developing small routines to help provide a sense of control and predictability, and personal activities or hobbies such as photography, music, or writing. Maintaining connections with home and family was deemed as essential by the experts in this study, by whatever means are available. Contact with family and friends was also identified as a key coping resource in a four-month FMARS simulation study (Bishop et al., 2010). Allowing time and space for some privacy was identified as important for maintaining adaptability in isolated, confined conditions. This was also found in the FMARS study, and is in line with studies showing that among Antarctica winter-over workers, introversion (and not extraversion) is associated with better performance and mission success (Rosnet, LeScanff, & Sagel, 2000; Wood, Lugg, Hysong, & Harm, 1999). Similarly, keeping a diary or journal can provide a way to safely "blow off steam" when interpersonal tensions rise, and to disclose personal thoughts that might be disruptive if expressed openly. Stuster (2010) among others has found that journaling is a valuable psychological aid for astronauts and others involved in ICE missions.

Setting realistic expectations before the mission was likewise regarded as a valuable coping strategy. If one sets low expectations in advance (for example, regarding opportunities to communicate with family during the mission; food and living conditions; opportunities to perform exciting, challenging tasks like EVAs) then there is less disappointment if things go wrong and the desired resources or activities are not available.

Some limitations of this study should be noted. Although the sample consisted of experts with extensive experience with ICE environments, including near-space missions, conditions that future astronauts may encounter on deep space missions such as to Mars at this point can only be imagined. There will no doubt be issues and challenges that have not been anticipated. Also, our sample is relatively small. The relative importance of the issues identified here should thus be taken as tentative. A larger sample of experts would be desirable to provide greater confidence in these rankings. In applying our results to the tasks and operations involved in space exploration missions, it should also be remembered that the experts we interviewed are presenting viewpoints based on their own experience and knowledge, and they may not be fully familiar with current NASA operations and design approaches.

Despite these limitations, our results merit careful consideration by those involved in the selection and training of astronauts, and also in the design and engineering of future spacecraft and habitats for long-duration missions. Astronaut living and work areas should be intelligently designed so as to counter as much as possible the major anticipated psychosocial stressors, such as confined living and work spaces and lack of privacy (Kitmanyen, Disher, Kobrick, & Kring, 2017). As one of our experts put it: "Give them less they have to adapt to!" Similarly, building in areas for group meals and recreation is important for maintaining crew social cohesion and teamwork (Kearney, 2016).

Along these same lines, providing crews with the means to control various parameters of the physical environment, such as temperature, lighting, and ventilation, can serve to mitigate the feelings of lack of control which can degrade crew morale and adaptive capacity (Bartone et al., 2017; Simon, Whitmire, Otto, & Neubeck, 2011). These are recognized issues in the NASA community, but are not always seriously considered in the equipment design process. The present findings once again underscore the critical importance of human factors considerations in planning and engineering spacecraft, habitats, equipment, and systems for future long-duration missions.

Conclusion

Through interviews with SMEs, this research has identified key individual and social factors believed to influence human adaptability on LDSE missions, as well as major stress factors and coping resources. While future experience with such missions will no doubt generate refined knowledge in this area, the present results provide some useful indicators of where to focus attention for improving and maintaining adaptability to the isolation, confinement, and environmental extremes that future astronauts will face.

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