

Human Factors in Space Exploration

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1. Introduction

The exploration of space is one of the most fascinating domains to study from a human factors perspective. Like other complex work domains such as aviation (Pritchett and Kim, 2008), air traffic management (Durso and Manning, 2008), health care (Morrow, North, and Wickens, 2006), homeland security (Cooke and Winner, 2008), and vehicle control (Lee, 2006), space exploration is a large-scale sociotechnical work domain characterized by complexity, dynamism, uncertainty, and risk in real-time operational contexts (Perrow, 1999; Woods et al, 1994). Nearly the entire gamut of human factors issues – for example, human-automation interaction (Sheridan and Parasuraman, 2006), telerobotics, display and control design (Smith, Bennett, and Stone, 2006), usability, anthropometry (Chaffin, 2008), biomechanics (Marras and Radwin, 2006), safety engineering, emergency operations, maintenance human factors, situation awareness (Tenney and Pew, 2006), crew resource management (Salas et al., 2006), methods for cognitive work analysis (Bisantz and Roth, 2008) and the like – are applicable to astronauts, mission control, operational medicine, Space Shuttle manufacturing and assembly operations, and space suit designers as they are in other work domains (e.g., Bloomberg, 2003; Bos et al, 2006; Brooks and Ince, 1992; Casler and Cook, 1999; Jones, 1994; McCurdy et al, 2006; Neerincx et al., 2006; Olofinboba and Dorneich, 2005; Patterson, Watts-Perotti and Woods, 1999; Patterson and Woods, 2001; Seagull et al, 2007; Sierhuis, Clancey and Sims, 2002). The human exploration of space also has unique challenges of particular interest to human factors research and practice. This chapter provides an overview of those issues and reports on some of the latest research results as well as the latest challenges still facing the field.

2. Space Exploration: Task and Environmental Context

The astronaut crew is the user population of interest in this chapter. Currently in American human spaceflight missions, the National Aeronautics and Space Administration (NASA) astronaut corps supports both the Space Shuttle and International Space Station programs. (In addition to NASA, an international community of scientists and engineers has contributed a distinguished body of work.) NASA generally

distinguishes between the roles of pilot, mission specialist, and payload specialist (NASA, 2009). The commander of a particular mission is also a pilot. The commander has overall responsibility for the safety and mission success of the crew and vehicle, and both the commander and pilot are responsible for the safe and effective operation and control of the vehicle. Mission specialist astronauts coordinate a variety of other operational areas, including system maintenance and repair, housekeeping, inventory management, waste management, crew activity planning, consumables usage, extra-vehicular activity (EVA) (also known as "space walks"), and scientific payload management. Payload specialist astronauts are trained for a specific scientific payload (onboard experiment). A fourth emerging category of space flight participants is space tourism, which is currently managed by the Russian Space Agency (e.g., Anderson and Piven, 2005).

A generic profile for a low-Earth orbit (LEO) human space flight mission, such as current Space Shuttle or ISS missions, can be described as the following sequence:

1. Launch and Ascent
2. On-orbit operations
3. Entry, descent, and landing (EDL)

A generic long-duration human space flight mission to a lunar or planetary surface can similarly be described as the following sequence:

1. Launch and ascent from Earth
2. Transit
3. EDL to lunar or planetary surface
4. Surface operations
5. Launch and ascent from lunar or planetary surface
6. Return transit
7. EDL back to Earth

It is important to note that long-duration missions are not different from LEO missions simply because they have a greater temporal duration – they also place more demands on the crew to adapt to different gravitational environments and to adapt multiple times to the vibration and acceleration profiles of the dynamic phases of flight (i.e., launch and ascent, and EDL).

The space environment is unique and deserves special scrutiny. As summarized in Figure 1, this environmental context is characterized by gravity, atmospheric, and radiation differences from typical Earth environments. In particular, hypergravity (gravitational forces greater than the usual "1 G" felt on Earth) is experienced during dynamic phases of flight, and hypogravity (ranging from partial-G on planetary surfaces to "zero G" on orbit) provides the experience of weightlessness that has numerous implications for crew health and performance. The atmosphere in space is a cold vacuum devoid of oxygen; as altitude (distance from the Earth's surface) increases, air density, pressure and oxygen content decrease. Another atmospheric consideration is dust on lunar and planetary surfaces; protection from dust both is important both for human health and equipment functioning (Park et al, 2006; Young, 2007). Finally, galactic cosmic radiation as well as episodic bursts of radiation from other

sources is a ubiquitous experience in space. Given that humans must be protected from atmospheric and radiation hazards, life support technologies are an integral part of the environments built for crews – space suits, air and ground vehicles (e.g., Apollo capsule, lunar rover, International Space Station), and habitats. Furthermore, dynamic phases of flight also cause crews to experience a variety of vibration and acceleration forces that impact crew performance. Finally, space exploration is an example of an isolated and confined environment, where the crew is physically separated from a variety of support systems, including friends and family, and generally confined together in a built environment.

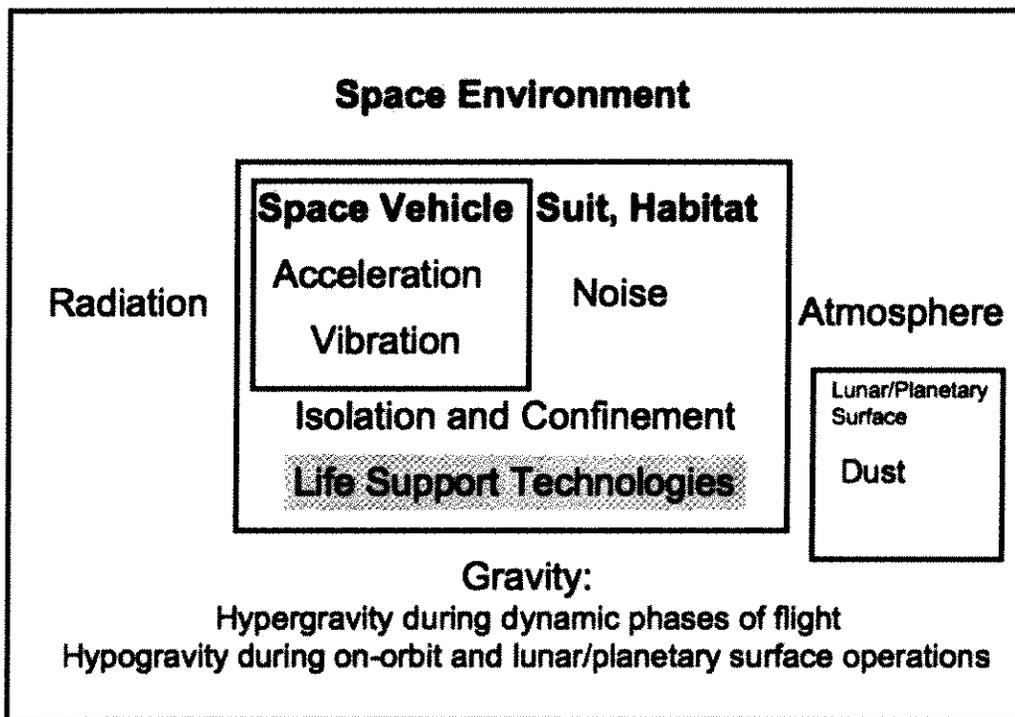


Figure 1. Overview of environmental factors.

Clearly, the dangerous environment of space demands that a great deal of attention be paid to crew health. However, a human factors perspective on space exploration further demands a focus on mission task performance. It is not enough that astronauts survive in space – they must be able to perform tasks such as piloting vehicles, rendezvous and docking, repairing scientific instruments such as the Hubble Space Telescope, building habitats and searching for resources on lunar and planetary surfaces, maintaining and repairing equipment and infrastructure, and so on. Figure 2 illustrates a selected set of topics from two broad frameworks: the NASA Bioastronautics Roadmap

(NASA, 2005) and stressors/stresses categories as organized by Kanas and Manzey (2008). Figure 3 summarizes these further as a health-task performance continuum.

NASA Bioastronautics Roadmap (2005)	Stressors and Stresses in Space (Kanas & Manzey, 2008)		
<ul style="list-style-type: none"> • Radiation • Human Health Countermeasures <ul style="list-style-type: none"> – Bone, Muscle, Nutrition – Cardiovascular, Immunology – Sensorimotor • Behavioral Health and Performance <ul style="list-style-type: none"> – Fatigue – Team Cohesion – Psychosocial Adaptation • Autonomous Medical Care • Human Support Technologies <ul style="list-style-type: none"> – EVA, Life Support Systems – Food Technology – Environmental Monitoring & Control – Space Human Factors Engineering 	<table border="1"> <tbody> <tr> <td data-bbox="779 567 1356 924"> <ul style="list-style-type: none"> • Physical Stressors <ul style="list-style-type: none"> – Acceleration, Microgravity, Radiation, Light/dark cycles • Habitability Stressors <ul style="list-style-type: none"> – Vibration, Noise, Lighting • Psychological Stressors <ul style="list-style-type: none"> – Isolation, Confinement – Danger, Monotony, Workload • Interpersonal Stressors <ul style="list-style-type: none"> – Crew size, Leadership – Personality, Culture </td> </tr> <tr> <td data-bbox="779 924 1356 1293"> <ul style="list-style-type: none"> • Physiological Stresses <ul style="list-style-type: none"> – Space sickness, Fluid shifts – Vestibular problems, Sleep disturbances • Performance Stresses <ul style="list-style-type: none"> – Disorientation, Visual illusions – Attention deficits, Psychomotor problems, Proneness to error • Interpersonal Stresses <ul style="list-style-type: none"> – Lack of privacy, Tension • Psychiatric Stresses <ul style="list-style-type: none"> – Adjustment disorders, Asthenia </td> </tr> </tbody> </table>	<ul style="list-style-type: none"> • Physical Stressors <ul style="list-style-type: none"> – Acceleration, Microgravity, Radiation, Light/dark cycles • Habitability Stressors <ul style="list-style-type: none"> – Vibration, Noise, Lighting • Psychological Stressors <ul style="list-style-type: none"> – Isolation, Confinement – Danger, Monotony, Workload • Interpersonal Stressors <ul style="list-style-type: none"> – Crew size, Leadership – Personality, Culture 	<ul style="list-style-type: none"> • Physiological Stresses <ul style="list-style-type: none"> – Space sickness, Fluid shifts – Vestibular problems, Sleep disturbances • Performance Stresses <ul style="list-style-type: none"> – Disorientation, Visual illusions – Attention deficits, Psychomotor problems, Proneness to error • Interpersonal Stresses <ul style="list-style-type: none"> – Lack of privacy, Tension • Psychiatric Stresses <ul style="list-style-type: none"> – Adjustment disorders, Asthenia
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Figure 2. Two frameworks for understanding the scope of human spaceflight.

Health-Performance Continuum: Examples

Health		Task Performance
Radiation effects	Orthostatic intolerance	Piloting
Bone loss		Surface navigation / way-finding
Muscle loss	Spatial disorientation	
Immuno-suppression	Visual processing	Equipment maintenance
	Cognitive processing	Scientific experiments
	Psychosocial adaptation	Medical care

Figure 3. Examples of health and human performance issues in space.

Because this chapter focuses on human factors issues rather than aerospace medicine issues, we will not indulge in a detailed discussion of radiation, bone, muscle, and immunology risks. However, because these issues obviously impact the ability of the crew to perform tasks, a short summary is appropriate.

As humans explore the lunar surface and outer space, the extreme danger of ionizing radiation to humans will require effective and available safety precautions. Human factors technologies may well aid in the development of accurate dosimeters of both radiation doses (Pisacane et al 2006; Wroe et al 2007) and their effects on humans (Cucinotta et al, 2001, 2002). Health, life expectancies, and performance capacities still need to be established as will the effectiveness of earth based countermeasures for ionizing radiation. Avoidance through shielding of radiation is essential in future spacecraft and habitats (Chang et al 2007; Cucinotta, et al, 2000; Guatelli, et al 2006). External shielding of the environment most closely aligns with a human factors focus on craft/habitat design, but there is also the need to aid the human body shielding for the deep internal biological tissues most sensitive to radiation. Current estimates of radiation poisoning indicate that long duration lunar exploration is quite possible with proper safeguards. A trip to Mars is problematic, with a

strong possibility of sickness-or death-inducing radiation exposures, given present shielding. There is also the possibility of mission failure or degradation because the crew member is unable to perform due to symptoms of radiation poisoning. Furthermore, the effects of radiation in space are complicated by the microgravity environment and how microgravity potentially degrades the effectiveness of the human immune system (see Jones and Karouia, 2008; Aviles et al, 2003; Cucinotta et al 2001; Shearer et al 2009) .

Medical issues related to “zero-gravity” environments that are key issues upon return to Earth include bone and muscle atrophy (including the heart), orthostatic intolerance, blood pressure change due to fluid shifts, and balance (neurovestibular) (e.g., Buckey and Homick, 2003; Davis et al, 2007). Post flight orthostatic intolerance, or the inability to maintain blood pressure in an upright position is well documented, especially in the first few days upon returning to the 1G of earth (Ball and Evans, 2001). This fall in blood pressure is accompanied by dizziness, fainting, and blurred vision. Although primarily a medical problem, this condition can make it difficult if not impossible for a quick egress from the landing spacecraft. Human factors analysis of the egress portal and moving in and out of the portal could facilitate a speedy egress during orthostatic intolerance, if needed. Acceleration forces change a variety of facets of cardiovascular performance (e.g., blood flow models of when hypoxia occurs (Banks et al, 2007), direct eye-level blood pressure, blood flow velocity in the superficial temporal artery (Krutz, Rositano and Mancini, 1975)). Space motion sickness and sleep disorders are fairly common among astronauts (Ball and Evans, 2001). Spatial disorientation is a clinical outcome of neurovestibular processes as well. Heat and dehydration are also issues (Nunneley, S. A., and Stribley, 1979).

The cognitive demands on the astronaut are similar to those of someone on earth in an extreme environment fraught with danger, doing complex work within a multicultural team setting, remote from [mission] control center and loved ones. Added concerns within the space environment are sleep/ circadian rhythm dyssynchrony, space motion sickness, affects on cognition through changes in neurovestibular /proprioceptive systems processing, and possible compromised immune system (Davis et al 2007). Sleep and or circadian rhythms are compromised by the changes in the diurnal period: a 45 minute day in low earth orbit, a very long period of sunshine or darkness on the lunar surface, depending on where on the moon one is. Microgravity means routine tasks make different demands. The astronaut cannot use gravity to help with physical tasks, such as turning a screw; tools float away if not held down. The nausea and general malaise of space motion sickness interfere with optimal task performance. The fluid shifts of microgravity on the neurovestibular /proprioceptive systems means that the crew member must work harder to overcome the cognitive deficits related to changed neurovestibular processing.

Space travelers must live inside a vehicle, suit, or habitat that protects them from the airless environment of space. These artificial environments themselves are another aspect of the physical environment that must be characterized. The key variables for this aspect of the physical environment for the crew are related to habitability and closed-loop life support systems.

Habitability is an overall concept that connotes subjective well-being, comfort, and productivity— many features of which are just as relevant to Earth-bound workplaces and homes. Specific issues in common with terrestrial concerns are thermal comfort, noise (Casali and Gerges, 2006), and freedom from bacteria, fungi, dust, fumes, and similar hazards (see Brauer, 2006). In addition, of course, spacecraft must also be designed to mitigate or have countermeasures for radiation, microgravity, and other unique features of the space environment. Spacesuits must be designed with the right anthropometric and biomechanical concerns.

Of special concern in space habitats, vehicles, and suits is the nature of the closed-loop life support systems. A closed environment confines humans to a small area with re-circulating air. Such an environment facilitates both not only the growth of normal flora but also of pathogenic bacteria and viruses. A spacecraft, lunar, or planetary habitat is similar to a terrestrial closed system. Several recent studies have produced evidence that spaceflight increases bacterial biofilm formation and antibiotic resistance (Nickerson et al, 2003; Allen et al, 2007). Microgravity also encourages viral reactivation in crew members while the closed loop system also affects the immune system. Unlike Earthbound systems, one cannot open the windows to get fresh air nor go outside to fetch fresh water. Therefore, hazards such as carbon dioxide poisoning and issues such as proper air pressure assume special consideration. Environmental closed-loop life support system (ECLSS) technologies perform such functions as managing air quality and recycling waste products into potable water.

2. Human Performance Issues in Space Environments

We focus on five aspects of human performance that are affected significantly by altered gravity and other aspects of long duration space missions and related to space human factors. These areas are neurovestibular, visual, motor control, cognitive, and behavioral health. Of course, a range of other issues in human performance also arises in space, such as auditory processing in noisy environments, automation interaction and the like. However, the analysis and countermeasures associated with those issues are not unique to the space environment and are not the focus of this chapter.

a. Neurovestibular

"Astronauts experiencing weightlessness often suffer from disorientation, motion sickness and a loss of sense of direction because their bodies try to adapt to the conditions of microgravity. Back on Earth, they must readjust to gravity and can experience problems standing up, stabilizing their gaze, walking and turning. Importantly, sensorimotor disturbances after gravity transitions are more profound as microgravity exposure duration increases. Such changes can impact operational activities including approach and landing, docking, remote manipulation, extravehicular activity and post-landing normal and emergency egress, and thus compromise crew safety and mission success." -- National Space Biomedical Research Institute; <http://www.nsbri.org/Research/Neuro.html>

Neurovestibular integration refers to the ability to orient the body, have smooth effective movement and respond appropriately to perceptual tasks. The body is amazingly adaptive as shown in clinical studies of individuals who have sensory deficits. Space adaptation to neurovestibular changes requires time and reliance on other sensory systems.

One of the more important bodily mechanisms in the neurovestibular response is the inner ear, specifically the otolith organs and semicircular canals. In addition, the proprioceptive system aids and facilitates the information received from the inner ear. Anyone who has tried to stand on one foot with eyes open and then eyes closed can attest to the increased difficulty of maintaining balance without the use of vision. Most of us automatically rely on what we perceive, but through training and experience pilots learn to trust their instruments over their neurovestibular and proprioceptive input.

In space, postural awareness and movement integration are affected by living in an environment of weightlessness. As crew members adjust to the

weightlessness of space and the resultant fluid shift in their otoliths and semicircular canals, they may have reduced capacity to integrate the body orientation and movement in a timely manner.

Over time, the human body learns to live in microgravity by adaptive bodily responses such as fluid shifts and neuromotor adjustments. Operational challenges occur in the first few days of spaceflight as the human has difficulties with gaze transitions (reading the written word, perceiving what is on a screens). Displays need to be adaptive to a wide range of temporary sensory deficits. Critical operations such as EVAs, Shuttle or Soyuz landings and dockings, robotic endeavors can be detrimentally affected by such changes. Human factors for spaceflight need to consider the implications of these neurovestibular changes for eye-head coordination, tracking data on a screen, locomotion, landing, and egress.

Sleep is affected as the crew member does not have the usual proprioceptive cues such as a pillow or a regular bed. Crew members sometimes report using a bunched up piece of clothing attached to the sleep restraints as a pillow the first several days of flight, even though the pillow is not needed in microgravity (Williams et al 2009). Space motion sickness (SMS), very similar to its terrestrial cousin, motion sickness, is a constellation of unpleasant events, dizziness, nausea, vomiting, associated with the changes in the vestibular and visual systems due to microgravity and acceleration. It usually lasts about 2 -3 days during a crew member's first flight, is unpleasant and interferes with optimal performance during that time. SMS can be controlled with pharmacological countermeasures.

Neurovestibular imbalances largely correct themselves over a few days, and it has been suggested that a simple mitigation is to wait to complete mission critical events such as extra vehicular activities for a few days. Neurovestibular challenges will re-occur as the crew member re-enters the 1 g atmosphere of earth, including the time of piloting the re-entry craft and leaving the space craft. Even during spaceflight, there can be disorienting events that can again temporarily affect performance and possible safety (Scheuring et al., 2009; Bacal and Clark, 2008).

Experienced military or commercial aviators are familiar with perceptual illusions, many of which are magnified if not caused by conflicting information to the neurovestibular system. Without an earth based, 1 g based spatial map, crewmembers can become disoriented during in-cabin emergencies, such as smoke or a hazy visual field. Returning to earth, these symptoms will reappear and then resolve, but again it is a time when optimal performance may be inhibited.

Many astronauts "experience illusions of self- and surround-motion, during both the zero-gravity and the entry and landing phases of space flight, with illusion intensity proportional to the length of time on orbit. While individual experiences vary, three types of self/surround motion disturbances are commonly reported: Gain disturbances (perceived self-motion and surround-motion seems exaggerated in rate, amplitude, or position after head or body movement), .. Temporal disturbances (the perception of self- or surround-motion either lags behind the head or body movement, persists after the real physical motion has stopped, or both), ... and path disturbances (angular head and body movements elicit perceptions of linear and combined linear and angular self- or surround-motion" (Stone, 2008; Oddsson et al, 2007, 2008; Jenkin et al, 2005).

In a spacecraft, visual acuity is affected by the darkness of space and brilliance of the sun, changes in the neurovestibular system, possible radiation effects, and the lighting system on the craft. In EVAs or lunar sorties, the crewmember copes with alternating bright light and deep shadows, depending on location to the sun (Kaiser and Ahumada, 2008). There is also the issue of where the astronaut is relative to the sun and resulting shadows or extreme light.

In EVAs or the lunar surface, the lack of atmosphere and therefore lack of atmospheric haze may make it more difficult to estimate distance, but should increase distance visual acuity. Since Mars has an atmosphere, there is atmospheric haze, analogous to that of an earth bound haze, although the color spectrum differs.

The lack of atmosphere on the moon means there is no blue sky, while the Mars environment is in the red spectrum. Lunar dust will also affect visual acuity as crew members explore the moonscape.

Static visual acuity and depth perception are generally not significantly affected as shown in a variety of in-flight studies, although subjective clinical reports indicate some decrements in near vision acuity (see Longnecker, Manning and Worth, 2004; Longnecker and Malins, 2006; Paloski et al, 2009).

Microgravity's effect of fluid shift and changes in the otolith regulation will affect vestibulo-ocular reflexes (VOR) temporarily. The VOR is crucial for ensuring that eye and head movements are coordinated to stabilize an image on the fovea. Space flight studies have shown that various VOR response properties for yaw, pitch, and roll head movements change during and after space flight, with a fairly large degree of individual variability (Paloski et al, 2009). It is generally expected that "accurate gaze stabilization during head movements (e.g., piloting/landing a spacecraft) will likely be performed less skillfully during or soon after G-transitions" (Paloski et al, 2009). The VOR is also involved in target acquisition tasks, where coordinated eye and head movements are performed. Space flight

studies have shown these processes are likewise affected; for example, Grigoryan et al (19xx) found increased latency in fixating on peripheral targets (also see Paloski et al, 2009). G-transitions also impact dynamic visual acuity, leading to blurred vision (oscillopsia)

Microgravity affects voluntary smooth pursuit eye movements; some studies have shown a decrement in visual performance but some have not (Andre-Deshays et al., 1993; Reschke et al., 1999; Kornilova et al, 1997; Moore et al., 2005; Paloski et al, 2009). Hand coordination tasks will show more errors (Reschke et al., 1999).

Changes to the human visual system caused by reduced gravity, fluid shifts, and changing day-night schedules affect sleep habits and ability to visually track across a field such as a computer monitor. A crew member returning to earth needs to re-adjust his or her visual system and related circadian rhythms.

Perceptual illusions are reported in space and earth and both environments involve the same principles: shape or orientation, reflectance and shadows, size/distance relationships. Kornilova (1997) reports that 98% of 104 cosmonauts reported illusions of orientation, position, or self- and surround-motion.

During launches, there will be increased gravitational forces, which can reduce or block peripheral vision. Some individuals may temporarily lose consciousness. Tunnel vision is the typical first symptom that pilots experience under +Gz acceleration forces (Banks et al, 2007). Under increased forces, tunnel vision progresses to "gray-out" and even to complete loss of vision.

The combination of hypergravity, vibration, and sustained and random acceleration can disrupt gaze stabilization (Stone, 2008).

In a recent meta-analysis of the literature, Conway et al (2006) found that whole-body vibration exerts substantial negative effects on perceptual task performance. Whole-body vibration exerts a more negative impact on performance accuracy rather than speed. A qualitative parsing of regimes (high versus low duration, intensity, and frequency, and their interactions) showed that as vibration frequency, intensity and duration increases, performance accuracy decreases.

b. Motor Control and Musculo-Skeletal Effects

"Changes on bone mineral density, muscle mass, and muscle function are the best-documented physiological effects of human space travel. ... [However,]

[I]imitations in data collection and analysis, the small sizes of databases, the lack of precise bone mineral density measurements...and the very high natural variations of makers of bone mineral density turnover all contribute to the difficulty of obtaining reliable data that would be useful for clinical decision making” (Ball and Evans, 2001, p. 42 and 45).

Spaceflight results in a loss of protein which in turn produces some wasting of weight bearing muscles. (Stein et al., 1999). The loss of muscle in microgravity is primarily focused in the legs and trunk. Muscle biopsies before and after flight show a decrease in the number of type I but no significant changes in type IIA and IIB muscle fibers. (Jaweed, 1994). Bone loss can also be serious, albeit with large individual differences (Buckey 2006). “The musculoskeletal system provides the framework and means of motion, locomotion, and force exertion for the human body” (Baker, et al, 2008). Physical performance across time in microgravity can deteriorate if the skeletal or muscle systems atrophy. Exercise while in flight reduces muscle and bone impairment.

The mechanical stresses experienced during vibration can affect practically all body systems. The body is most sensitive to vertical (Z-axis) vibration and the most common health issues from prolonged exposure are back pain and back disorders. Many effects are associated with the cardiovascular and thoracoabdominal visceral systems. Table 1 summarizes empirical data on symptoms associated with different frequency regimes.

Table 1. Symptoms experienced at different frequencies (Hz) (Smith et al 2008)

Symptom	Frequency (Hz)
General discomfort	4.5 – 9
Valsalva	4.5 – 10
Respiration	4 – 8
Abdominal pain	4.5 – 10
Lumbosacral pain	8 – 12
Muscle tone	13 - 20

In a recent meta-analysis of the literature, Conway et al (2006) found that whole-body vibration exerts negative effects on both continuous and fine motor control task performance. Whole-body vibration exerts a more negative impact on performance accuracy rather than speed. A qualitative parsing of regimes (high versus low duration, intensity, and frequency, and their interactions) showed that as vibration frequency, intensity and duration increases, performance accuracy decreases.

A variety of visual-vestibular signals and reflexes are adversely affected during the microgravity and vibration and acceleration forces of spaceflight (Stone, 2008). In particular, disrupted gaze stabilization and perturbation of the body compromises manual control performance. Disrupted motor control is also a critical issue during transitions between zero-gravity and gravity; motor control systems (manual and postural) are initially inappropriately tuned for weightless limbs and body, leading to an increased likelihood of motor errors, postural deficits, and ataxia (Cohen, 1970; Cohen and Welch, 1992; Reschke et al. 1999).

c. Cognitive Effects

Historically, most studies of astronaut health are dominated by medical concerns such as bone loss and cardiovascular functioning. Cognitive task performance in space has been a relatively little-studied area.

Increased +Gz acceleration, especially short-duration and rapid-onset forces, leads to less blood flow to the brain (cerebral hypotension) that can lead to a set of cognitive impairments known as “Almost Loss of Consciousness” (A-LOC) (Banks et al, 2007). A-LOC is characterized in part by disorientation, poor word formation, and amnesia. Further cerebral hypotension beyond A-LOC can lead to G-induced loss of consciousness (G-LOC). G-LOC can be relative and recoverable (sometimes experienced by subjects as very short dreams (“dreamlets”)) or be absolute (i.e., unconsciousness).

Cognitive assessments during long-duration space flight have been performed using the objective, computer-based tool Cognitive Assessment Tool for Windows or WinScat. The WinSCAT, based on several Automated Neuropsychological Assessment Metrics (ANAM) tests, was developed as a neuropsychological screen for crew members who may have suffered a head injury, exposure to toxic gas or some physical insult. The astronaut establishes a baseline performance score before flight. During flight normative data are collected every 30 days. In a few cases, results have been off nominal, showing some equivocal effects related to short-term memory and reaction time. The WinSCAT was not developed as a performance measure of the effects of sleep deprivation or fatigue (Kane, et al. 2005)..

In the near future, the Psychomotor Vigilance Test (PVT) Reaction Self Test developed by David Dinges, will be flown on the ISS to evaluate the sensitivity of the PVT Reaction Self Test to measure performance decrements due to fatigue and circadian disruption as well as any effects from sleep medication routinely taken during spaceflight missions. Previous work with the PVT on NASA Extreme Environment Missions (NEEMO) in an underwater habitat showed that the PVT has the needed validity and psychometric properties to serve as a screen of neurobehavioral performance in space (Dinges, 2008).

Anecdotal evidence from returning crew members indicates that some astronauts experience a temporary cognitive impairment sometimes called “Space Fog” or “Space Stupids.” This experience most often occurs as a part of

the temporary sequelae of space motion sickness as the astronauts must use cognitive effort to compensate for bodily and spatial disorientation (Clement and Reschke, 2008). Usually, as the body adjusts to microgravity the cognitive impairments related to "Space Fog" disappear.

d. Behavioral Health and Performance

Behavioral health and performance (BHP) is a concept that deals with psychological and some psychiatric issues in long-duration human space flight, such as psychological aspects of crew selection and training and teamwork performance. BHP also refers to a set of organizational arrangements, such as the international Spaceflight Human Behavior and Performance Working Group (SHBPWG) that consists of operational groups from European Space Agency (ESA), Japan Aerospace Exploration Agency (JAXA), NASA, and the Russia Federal Space Agency (Duncan et al, 2008).

Within NASA, the BHP group at the Johnson Space Center consists of psychiatrists, licensed psychologists, and behavioral specialists. The JSC BHP operational group focuses on operational issues of selection into the astronaut corps, psychological support of missions and behavioral medicine, primarily for the ISS. Operational psychology (op psych) is one aspect of the JSC BHP operational group. It provides psychological services and mission preparation for astronauts before and during a mission as well as providing debriefings after missions. There is a family support office that focuses on family function, coordinating with local schools, providing practical planning and multicultural training. Other training topics developed by operational psychology include self-care, conflict management, and briefings on psychological factors of long duration missions. During flight, op psych facilitates weekly private family conferences. It also provides an Internet protocol phone on the ISS, ham radio, e-books, e-videos, email, a personal web page on ISS, and care packages sent up on cargo relays. Op Psych and B-Med are involved in astronaut selection but they are not involved in specific mission crew selection. Behavioral Medicine (B-Med) is another service of the JSC BHP operational group. B-Med provides clinical care for astronauts as well as training for crew Medical Officer and Flight Surgeon. In-flight monitoring includes private psychological conferences and the WinSCAT neuropsychology screen in case of physical injury or exposure to toxic environments.

BHP was cited as one of the three major concerns in the "Safe Passage" report (Ball and Evans, 2001). Long-duration space missions will isolate the crew from their families on Earth, will confine the crew together in a vehicle and habitat for some months or years on end, and are likely to be environments lacking in privacy and abounding in noise.

The original Mercury project looked at astronaut proficiencies with no knowledge of the challenges of spaceflight. Hence, the first astronaut candidates were

chosen from the group that would have had the closest experiences with space, test pilots. Within this group, psychosocial competencies were extensively evaluated. Today's astronauts have a number of functions to perform and we have some knowledge of the effects of spaceflight on the human. All astronaut candidates must pass an extensive physical exam and undergo about five years of training before a mission. Space participants or tourists also pass a physical exam and must successfully finish the abbreviated Russian training program.

Laura Galarza, Al Holland and others (Galarza et al 1999), using qualified subject matter experts and accepted Society of Industrial and Organizational Psychology job analysis procedures, developed a model of core psychosocial factors important for long duration space flight environment: performance under stressful conditions, mental/emotional stability, judgment/decision making, teamwork skills, conscientiousness, family issues, group living skills, motivation, communication skills, and leadership capabilities.

Given the small number of astronauts who have flown on long duration space missions, it is difficult to quantify the optimal knowledge, skills and aptitudes needed. In addition, different missions have different assignments, so technical competencies (geologist versus engineer) vary across missions. Nonetheless, each person must know specific skills, ---e.g., pilots must know how to pilot --and know how to work in a team setting that is both confined and isolated with little privacy from each other (Kanas and Manzey, 2008).

The image of a crew member floating inside the International Space Station , spinning through portals into the different national modules belies the complicated reality of living on the ISS. Astronauts must learn which way is "up" for each of the modules, as the modules are not all oriented in the same direction. Between cargo flights, the station becomes cluttered. Clutter means moving things to get to the needed tool and everything takes a little longer, possibly straining the patience of the crew. An astronaut completing an EVA on the end of the Canadian built robotic arm is another breath-taking image. Inside that EVA suit, the astronaut is very cold or very hot, fingertips become bruised by the gloves, exhaustion sets in as every movement must be adjusted for the microgravity of space, tools must be secured. The EVA crew member communicates with the member inside the space station, sometimes with and sometimes without visual contact. These tasks involve the usual earth bound issues of remote communication, robot- human teams, display of information, warning and signals, but within the environment of microgravity, potential radiation spikes, and a self sustained system of fresh air (Aoki, Oman and Natapoff, 2007).

Lunar sorties present additional complications. As seen during the Apollo era, astronauts must learn to transport themselves across very dusty and abrasive surfaces. Since the Apollo time, gloves have been improved and there is continual work on the EVA suit. Nonetheless, lunar dust in the lungs and

habitats remains a risk (Prisk, 2000), visual tasks must deal with the shadows and reflectances on the moon, transporting across low gravity valleys and slopes – all remain challenges for physical and cognitive tasks.

Mir and now the International Space Station consist of multicultural crew members. Crew members professional backgrounds range from pilot to school teacher. The ISS modules were built by various nations. As such, the complexity of spacecraft and ground support teams has increased. Multinational corporations are familiar with the challenges of working with multi-cultural groups. The same issues exist for the crew members in space (Kozłowski and Ilgen, 2006; Matveev and Nelson, 2004).

At the same time, the dual stresses of isolation and confinement reduce face to face social contact to those two to five other people aboard the craft. Variables that facilitate interpersonal conflict under such conditions are psychological incompatibility; ill defined or unbalanced role structure; cliques; less capable leadership behaviors; and lack of privacy. (Nicholas and Penwell, 1995; Palinkas et al., 2000; Stuster, 1996; Suedfeld and Steel, 2000)

The aviation community has long been aware of the need for optimal cockpit - ground interaction. The same issue exists for space – ground interaction. Kanas, discusses crew-ground interactions, noting the importance of handling possible ingroup versus outgroup issues, displacement, possible lack of empathy, scheduling overloads, and aspects of crew autonomy. Comparing MIR to the ISS experience, Kanas and his colleagues showed the complexity of comparing Americans and Russians by crew or ground location. The ISS study indicated that there were no major mood changes across length of time in spaceflight. Similar to earlier studies with Shuttle /Mir Participants, there was evidence of displacement for both crewmembers and mission control personnel (Kanas and Manzey, 2008).

Many of the issues in spaceflight individual and team performance are the same as those in ground based operations and studies and will not be a focus of this presentation. Only recently has there begun a systematic study of psychosocial adaptation in spaceflight. The BHP research element has identified gaps in knowledge relating to spaceflight psychosocial and behavioral performance characteristics.

Degradations in performance because of sleep deprivation, circadian desynchrony, fatigue, and work overload are well documented on earth. (Barger, et al. 2005; Czeisler et al. 1999; Dinges, et al. 2004; Klerman et al., 2007). These findings have not been studied systematically on low earth orbit until very recently. Light requirements and light as an activating stimulus are now being

studied to determine if light can be a non pharmaceutical arousal stimulus (Brainard et al. 2008; Lockley et al., 2004, 2006, 2007).

Teamwork, selection, training and psychosocial adaptation are other areas that have received extensive focus in earth based research, but very little research attention in the space program. Given the small sample size of the astronauts, psychosocial studies of personnel in extreme earth environments have been used to provide insight into the possible challenges of long duration spaceflight. The Antarctica has provided some clues, but it must be remembered that there are few articles on Antarctica and there are differences, such as group size and the level of privacy (Galarza et al, 1999; Lugg, 2005; Schmidt et al, 2008; Stuster, 1986, 2007). In space missions, crew communication and interpersonal tensions have been noted in a variety of studies (Kanas and Manzey, 2008).

3. Recent Examples of Human Factors Work in Space Exploration

Human factors expertise has contributed to numerous improvements for crew systems within NASA. The updating of NASA standards for human spaceflight and the accompanying Human Interface Design Handbook (HIDH) is an Agency-wide effort to establish standards for human performance and human-systems integration (Russo et al, 2007). Many issues remain to be tackled in the new Constellation architecture (see McCandless et al, 2006).

a. Human performance under vibration and acceleration loads

The current Constellation architecture identified a key technical problem in 2007: thrust oscillation transmitted from the Ares launch vehicle to the Orion crew module. This led to a series of human factors studies to characterize human performance under a combination of vibration and acceleration loads representative of the thrust oscillation problem (Adelstein et al 2009a and 2009b) that built upon 1960s-era studies of human performance under vibration and acceleration (e.g., Vykukal, 1968; Vykukal and Dolkas, 1966). To characterize the vibration environment as it applies to humans, it is important to distinguish the type of translational and rotational vibration, as well as the frequency, intensity (or amplitude), duration, bandwidth, and peak value of the vibration (see Griffin, 1978; Griffin and Lewis, 1978; Seagull and Wickens, 2006). In human factors, the dynamic system of interest is the human body – both the entire body itself (“whole-body vibration”) and body parts (Brauer, 2006). Both the International Organization for Standardization (ISO) and the American National Standards Institute (ANSI) have published guidance on whole-body vibration.

In addition to vibration, astronauts are subject to a variety of acceleration forces during dynamic phases of flight. A key factor in the analysis of acceleration forces is its vector relative to the human body, typically described as in Table 2 below (see Banks et al, 2007). Thus, given that a person is seated upright, the x-axis is “chest-to-back”, the y-axis is “side-to-side”, and the z-axis is “head-to-seat” or (if standing upright) “head-to-toe”. In spacecraft during launch and ascent, the crew is typically seated with their backs to the “floor”, thus experiencing the majority of acceleration forces through the chest (i.e., +Gx) during launch and ascent.

Table 2. Directions of Acceleration

G	Description
+Gx	Forward; “step on the gas”
-Gx	Backward; “step on the brake”
+Gy	Press against left arm rest
-Gy	Press against right arm rest
+Gz	Down; “heavy in the seat”
-Gz	Up; “light in the seat”

The thrust oscillation human performance studies conducted by Adelstein et al (2009a and 2009b) studied both vibration and combined vibration and acceleration forces, with the aim of quantifying the impact on human performance and thus creating more rigorous human-systems integration requirements. The main dependent variable of interest was the ability to read text from computer displays, with the independent variables of vibration and Gx-loading levels and two alternative display font sizes consistent with the Ares-Orion profile. The studies found a significant performance decrement with higher levels of vibration and Gx-loading, significant interaction effects with font size, and a fairly high degree of individual variability in performance.

b. Other human factors design improvements

Human factors engineering has led to numerous improvements in procedures and procedure support technologies aboard the International Space Station (Peacock et al, 2006), for example with medical operations procedures and checklists (Holden, 2008) and the evaluation and redesign of cue cards for respiratory medical procedures (Byrne, Hudy Whitmore, and Smith, 2001). Based on an analysis of ISS crew debriefings, Rando, Patel and Duvall (2007) conducted usability evaluations of a variety of caution and warning (C&W) designs and recommended a variety of design improvements.

In the late 1990s, NASA embarked on a program to upgrade the Space Shuttle avionics and crew displays – the Shuttle Cockpit Avionics Upgrade. Human factors was an integral part of the design and evaluation of concepts. The upgraded display concepts included new horizontal situation indicator displays, integrated information about ascent trajectory, propulsion status, and data processing, and consistent use of color coding and other features to improve crew situation awareness and performance (Hayashi et al, 2005). In the current Constellation architecture, the Orion crew module will use “glass cockpit” displays, electronic procedures, and other modern technologies. Concepts for the Orion crew cockpit have included the design of new fault management displays that integrate information to support more effective crew coordination and performance (Hayashi et al, 2006).

Interactive systems to support payload operations will be required for lunar and planetary crewed missions. Current ground data systems for robotic missions are a useful analog for these future concepts. One example of using state-of-the-art human-computer interaction methods for design is the Phoenix Science Interface (PSI), which was used for tactical activity planning by the science team for the Phoenix Mars lander mission (Fox and McCurdy, 2007; McCurdy et al, 2006).

4. Future Work

The future of human space exploration continues to be an exciting topic of debate. In addition to vigorous debates about the requirements for new design reference missions (e.g., seven-day lunar sortie missions; human exploration of Mars; human exploration of asteroids or other near-Earth objects) and the resulting need for analog studies (e.g., studies in the extreme environments of Earth such as the Haughton-Mars crater on Devon Island in the Arctic, the Utah desert, or underwater “NEEMO” missions), there are still numerous outstanding questions about the psychosocial implications of long-duration missions; human-robotic teaming for exploration (e.g., astronauts driving vehicles out to explore, coordinating with robotic partners, etc.); and operational implications of “in situ resource utilization” (ISRU). In addition to strategies and tactics of exploration, the three great tragedies of the NASA human spaceflight programs – Apollo 1, Space Shuttle Challenger, and Space Shuttle Columbia – have led to a great deal of analysis of macro-ergonomic issues such as organizational culture, safety culture, process complexity, politics and power (e.g., Tomkins, 1993, 2005; Starbuck and Farjoun, 2005; Vaughan, 1996; NASA, 2003).

One key research issue that continues to be relevant is the use of existing data. There are numerous archives of heterogeneous data sets ranging from astronaut

biographies (e.g., Hansen, 2006; Jones, 2007; Mullane, 2007), to oral histories, to telemetry records, to online archives such as the Life Sciences Data Archive hosted at NASA Johnson Space Center, to technical reports about human system integration requirements and lessons learned. Examples of the latter include the "Apollo experience reports" about crew station design (Allen and Nussman, 1976), displays and controls (Langdoc and Nassman, 1975), procedures (Kramer, 1973), hand controllers (Wittler, 1975), restraint systems (Drexel and Hunter, 1973), experimental support (McKee, 1974), stowage (Hix, 1973), lighting (Wheelwright, 1973), simulation-based training (Woodling et al, 1973), and provisions and equipment (McAllister, 1972). These data sets continue to be used for formulating requirements for the new Constellation missions (e.g., Scheuring et al, 2007). However, there is a continued need for better "data mining" of these resources to make the best use of that knowledge for current and future missions. A corollary is that current requirements should also include improved methods and tools for human factors data acquisition and analysis.

Another key research issue is what might be called multi-level modeling: that is, more complete integrated models of human performance that span the physiological, psychological, social, and task performance aspects of human behavior and performance. Finally, improvements in human-centered design methods and tools, and better human-systems integration throughout the lifecycle, are needed in the NASA environment.

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