National Aeronautics and Space Administration

Research Campaign:

The Three Body Problem of Human Factors in the Space Environment

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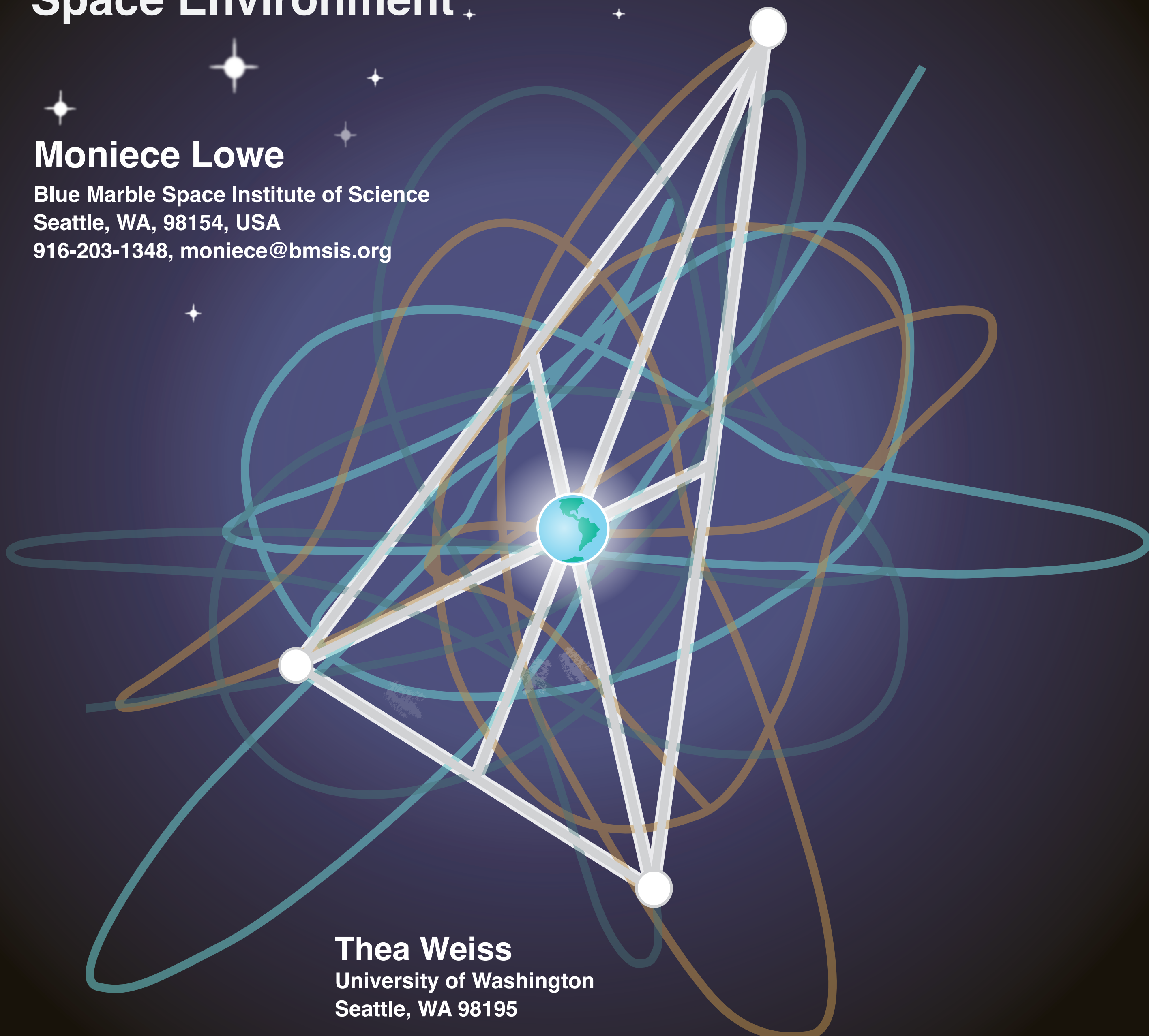

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Background: Fifty-five years after the Apollo Moon landings, NASA aims to send its counterpart - Artemis – with the first female and the first person of color to establish a Moon base. Artemis is one step on a long-term mission to Mars. Meanwhile, NASA will continue to avail itself of research opportunities on ISS, Lunar Gateway, and a new class of commercially operated orbital stations. Following on decades of research from Low Earth Orbit (LEO) and analog ground studies, now is the time to integrate historically distinct fields to advance the science of human-led missions in space. Each mission, from Artemis to Mars, increases the time astronauts are exposed to both known and unknown hazards, e.g., radiation and microgravity. Missions that extend into years can expect to see a dramatic effect on health, such as loss in bone architecture and susceptibility to fracture and muscle atrophy, in addition to a variety of other unforeseeable physiological and psychological alterations. Less well understood, but equally important, are the co-occurring social and cultural stressors that will impact crews who are confined to a small habitat for months and eventually years at a time. This decadal addresses the need for a concordance between individual astronauts, space mission team, and habitat and technology utilizing an integrative approach through Human Factors.

Goals, Objectives and Investigation

1.) Individual Astronauts

Due to the exclusive nature of human space flight, current astronaut data is sparse and lacks diversity regarding sex, race, and ethnicity (Mark et al., 2014; Smith et al., 2020). Historically, women have only made up 11% of astronaut-led missions, just 16% of ISS visitors, and none have gone beyond LEO (Mark et al., 2014). Likewise, no missions in which NASA has participated have featured even a majority of non-white individuals. There is a discontinuity in details about ethnic and racial effects on health outcomes under space conditions (Smith et al., 2020). Most human data about health and mission risks are most relevant for white males. Animal studies are beginning to delineate space-specific sex differences, e.g., cognitive susceptibility to galactic cosmic radiation exposure, where male mice are more likely to show decrements in memory and heightened anxiety (Krukowski et al., 2021). Health discrepancies between males and females have long been documented in other fields (e.g., cardiopulmonary, immunology, bone density, etc.) while race/ethnicity as a variability in medical risk and optimization has become an emerging area of study (Hall et al., 2020; Williams et al., 2019). Collectively, these biological distinctions should be considered an important factor for understanding health risks and optimization in space.

Health implications for long-duration space missions increase risk to multi-organ systems and tissue types, resembling rapid aging (Vernikos & Schneider, 2010)- leading to long-term physical changes that can alter an astronaut's baseline functioning (Lee et al., 2020). The consequence of long-term space exposure beyond LEO (e.g. microgravity and galactic radiation) increases risk of disease, injury, or inability to carry out mission-critical tasks. Studies across analog, ground base, and fields outside of space research have demonstrated that stress and isolation can also cause health decrements that impact cognition, immune response, and wound healing (Rubinstein et al, 2021; Rai et al., 2012) and will likely be a confound to health risks. The biosocial-emotional entanglement, although defined in the human research roadmap for *Risk of Adverse Cognitive or Behavioral Conditions and Psychiatric Disorders*, remains largely unaddressed in space research and currently offers no complementary countermeasures.

Sex, Race, & Ethnicity: Sex is a unique genetic marker which relates to a range of physiological pathways and health outcomes. Notably, one model frequently used to understand physiological alterations due to microgravity is accelerated aging, which share features such as loss in bone, muscle, and neurological alterations documented in astronauts (Vernikos & Schneider, 2010). The human lifespan is an undeniable feature of sexual dimorphism, favoring the female sex with longer lifespans and slower molecular aging compared to males (Hägg & Jylhävä, 2021). In addition, regarding race and ethnicity, research into a range of health differences suggests distinctive physiopathology and health benefits, such as bone density (Farrell et al., 2020; Araujo et al., 2007). It is imperative to study diverse crews that can distribute the burden of loss of functioning for the highest risk factors associated with long-term missions from LEO to the Moon. Research into physiological adaptions unique to race, ethnicity, and sex under the extreme environment of space would benefit the terrestrial goal of health-outcome equity among women and people of color.

Use of Aging & Ableism Models: Responsible habitat design and protocol development for space must be founded on known health challenges, providing a comprehensive approach to long-term astronaut missions both in LEO and beyond without risk of an ableist stance. Disability can be better understood as a mismatch between physiology and environment. All humans in space, especially those experiencing the cumulative effects of prolonged periods in space, can be viewed as disabled, a fact recognized by ESA's current Parastronaut Study (ESA 2021, Baker 2021: Heinicke et al., 2021). Given the anticipated physiological changes - and their resulting limitations - that will arise for long-term missions it is imperative to gain a greater understanding of how astronauts are able to engage with their environment over time in situ. Analog studies utilizing healthy, disabled, and aged persons with limitations such as muscle atrophy, bone loss, and neurological alterations in habitat configurations used for the ISS, Lunar Gateway, and Lunar Base can provide a model on how astronauts may change their interaction with space habitats over time and manage mission specific tasks. This model can then be tested on missions across ISS and Lunar Gateway to determine if changes in biomedical functioning alter how astronauts engage with their surroundings, providing early indicators of when individual astronauts might require intervention or increased support. Engagement with the extensive work of scholars in disability studies and science and technology studies (STS) will provide vital context for appropriate experiment design and interpretation of the results.

Psychological Evaluation Gold Standards Established for Space: Psychological assessments are invaluable tools (Meyer et al., 2001). Currently, behavioral health evaluations for the space sciences have a validation issue. All accepted assessments have been designed and validated for populations quite different from astronauts and their stressors. There needs to be dedicated research validating gold standard psychological assessments and interventions for mental and cognitive health changes that are salient for the unique confounds of long-term space missions and missions outside of LEO (such as health degradation, pain management, use of countermeasures, amount of time spent in an extreme environment, etc.). It is essential to organize and study a battery of tests that can provide a holistic interpretation of astronaut functioning, without disturbing daily tasks or interfering with individual and group functioning (e.g., reporting on peers' emotional states). Assessments for anxiety and depression should be prioritized as they overlap with many psychiatric disorders and medical complications. These assessments should be developed in ground analog environments with populations that match astronauts, including screening for mental health histories and family histories, and co-occurring loss in physical functioning that are consistent with risk factors for astronauts (bone loss, muscle atrophy, vision challenges, immune compromised, and pain). Such research should prioritize female and diverse ethnic/racial participants. Once standardized psychological assessments for astronauts in space has been validated on the ground it will be essential to test in situ, for long-term missions and missions outside of LEO. The result of these findings may inform best practices for psychological monitoring and treatment for astronauts exposed to long-term, deep-space missions, in addition to chronically ill and aging populations on Earth.

Psychological Counter Measures: Meditation and mindfulness-based practices have been studied for decades demonstrating a range of benefits: lowering stress biomarkers, elongation of telomeres, pain management, decreasing depression, decreasing anxiety, correcting sleep disturbances, enhancing attention, and increasing well-being (Behan, 2020; Basso et al., 2019; Schutte et al., 2020). Animal and astronaut studies have demonstrated that the space environment poses a risk of psycho-emotional and cognitive decrement that is most likely to occur in long-term and deep space missions (Rubinstein, 2021, Acharya et al., 2019). In the next decade meditation and mindfulness practices should be examined across mission types from the ISS to the Lunar Base, in order to determine efficacy by evaluating duration needed to gain therapeutic benefit on behavioral/medical measures and the unique benefits of practicing alone or in a group. It will also be important to determine if these interventions will prevent dramatic telomere shortening, a biosignature of genomic instability, when astronauts return to gravitational surfaces (i.e., Earth, Moon, Mars), as found in the twin study (Luxton et al., 2020; Luxton & Bailey, 2021).

2.) Team: Ground and Astronaut

Team productivity and successful self-organization are dependent on meaningful communication, trust, and integration of individual expertise. In the space environment, team formation and maintenance face many challenges, including noise; disruptions in mental and physical health; language barriers; variation in cultural backgrounds; and impaired transmission of body language (Kanas et al., 2002; Cohen, 2000). Team cohesion is essential for amplification of goal-focused behavior; positive team cohesion engenders motivation among its members and effective task completion. Teamwork is not only measured by completion of tasks, but also by how individual members interact and self-organize during times of work and rest. While successful task completion is the most common way to measure success of a team, changes or failures in this measure would indicate a problem well after the team dynamics had begun to break down.

Unobtrusive Measures of Group Health: A potentially more salient and less disruptive measurement in team dynamics and long-term trends would assess how astronauts utilize their environment to congregate and separate over the course of a mission. By studying how teams utilize their natural environment to create physical barriers between them and others or to create shared space would provide a model for successful team assembly and maintenance. Tracking astronauts in situ while cross-referencing with other health metrics and crew makeup will assist in defining patterns required for productive team development. This can easily be studied by providing wearables and context cues of where in the spacecraft an individual is and how much time they spend around other crew members. The hardware can be validated in extreme analogue environments and then tested across multiple missions of varying length and distance to better understand how duration impacts how astronauts experience their habitat.

Immersive Team Cohesion Training: Providing realistic training to develop successful team cultures has been shown to be highly effective in providing positive team outcomes in task completion and team maintenance (McEwan et al., 2017). Within space aeronautics there are two distinct elements to the space mission team: ground control and astronaut crew. Cooperative functioning is essential for the safety of the astronauts and successful mission completion (Bell et al., 2019). In addition, with missions extending beyond LEO and with increasing duration, astronaut crew members will have to rely on each other for social support and successful space adaption (Bell et al., 2019). Over the span of long-term missions ground crew and astronaut crew will be required to be more adept at identifying behavioral health issues and risks under complex conditions, such as coinciding health changes or sleep disturbances. Training for such complicated interactions is critical for providing appropriate interventions. Virtual reality (VR) can provide a range of training modules for multifaceted scenarios, including having the user experience impairment in physiological functioning such as vision loss. Re-trainings on long-term space missions should be tested, utilizing VR, aboard ISS, Lunar Gateway, and Lunar Base assessing efficacy in reducing team conflict and preventing the creation of "out" vs. "in" groups, fostering trust across teams, and preparedness for supporting crew members during crises.

3.) Habitat and Technology

The complete set of symbolic structures that organize social behaviors, including beliefs, traditions, and roles, as well as types of objects and architectures and their design and implementation can be characterized as "culture." Cultural maladaptation negatively impacts crew well-being and mission success. Recent NASA-sponsored studies in environmental and behavioral psychology have begun to include these features in their discussions (Whitmore et al*.,* 2013; Slack et al*.,* 2016; Blackwell Landon et al., 2016; Blackwell Landon et al*.,* 2020). Kearney (2015) listed the following culture-inflected risks related to habitats: inadequate privacy, inadequate social space, inadequate habitat flexibility/reconfigurability, crowding, incompatible layout, inadequate stowage system, insufficient net habitable volume, inadequate workspaces, excessive background noise, and inadequate lighting. Social science research relating to culture (e.g., anthropology, post-occupancy studies in architectural design, etc.) is crucial for providing needed insights in these areas.

Concomitantly, Human Systems Integration Architecture (HSIA) research seeks to understand how HSIA can address adverse outcomes- such as depression, changes to sensory perception, and behavioral changes (Risk of Adverse Outcomes, 2021)- relating to central nervous system, behavioral, and sensorimotor (CBS) systems. This integrated CBS approach mirrors NASA HRP's cross-cutting CBS Integrated Research Problem Statement and Implementation Strategy evidence reports (NASA HRP Communications, 2019a; NASA HRP Communications, 2019b).

Cultural Assessment as Measures of Habitation Adaptiveness: NASA's Human Research Roadmap does not currently recognize the contribution of cultural features to identified risks for long-duration missions. Key areas of habitat research include organization of spaces as mono- or multi-functional for work, leisure, storage, hygiene, privacy, etc.; ergonomics, and especially the design of facilities for comfort and habitability, not just survivability; the use and adaptation of spaces, including alteration, personalization, and change in use over time; the tension between the design of tools and other items either for flexibility or for specialization for a specific purpose; and the identification of disjunctions between how spaces and objects are planned to be used by designers, and the lived reality of crews in space habitats. Some research by social scientists has already begun in these areas, although it has been constrained by access to data and available funding (Buchli 2021). Investigators have focused on terrestrial analog environments such as the NEEMO underwater habitat (Olson 2018), others on ergonomics and privacy (Aiken 2014) or the effects of gravity - or its absence - on human cultural and social interactions (Parkhurst & Jeevendrampillai, 2020). Stuster (2010, 2016) performed a NASA-sponsored study of crew-authored journals describing their experiences living on ISS, revealing numerous areas for improvement. His work is being supplemented by the CSA-sponsored sociology/psychology study "At Home in Space" (CSA, 2017). The ongoing International Space Station Archaeological Project (Walsh & Gorman, 2021) has studied crew personalization of a space habitat through the creation of visual displays on ISS (Salmond et al*.,* 2020; Walsh et al., 2021); the distribution of groups of crew members across ISS modules by gender, nationality, and space agency affiliation (Walsh et al., 2021b); and how the discard of different kinds of items from ISS reveals the meanings these items have taken on for crew and ground staff (Walsh et al*.,* forthcoming). This work has shown the importance of allowing crew to contribute to some aspects of the design and layout of their habitat (including during the mission), revealed the need to optimize organizational systems for work that maximize the efficient use of space by all crew members, and introduced new ways of understanding crew experiences in space.

Future work should focus on continuing to define important cultural features in the space context and development of experiments that investigate how spaces are used (for storage, for leisure, for work, etc.), how crew members are able to create space for privacy and personal rapport, and how crew adapt available items to new uses or adapt themselves to the items available to them and how critical these adaptations are for crew collective and individual well-being. The most significant venues for this research will necessarily be the available platforms for long-duration missions, namely ISS and, eventually, the Lunar Gateway station, as well as the proposed new generation of commercial space stations.

HSIA Technologies for Prevention and Countermeasure to CBS Risks: We suggest a systems-theory approach to develop and test HSIA technologies. This approach affords a holistic method to provide for human psychophysiological enhancement, protection, and interventions crucial for achieving long-term mission goals. Research that investigates how HSIA technologies can adapt across the duration of the mission as well as to individual crewmembers to provide automatic and individualized care should be prioritized. The integration of a comprehensive health monitor would reduce cognitive load by limiting crewmember decision-making regarding countermeasures (Mesko, 2018). We suggest investigating how HSIA technologies could address risks to the tactile, vestibular, proprioceptive, and interoceptive systems. Technologies that integrate haptic feedback, proprioceptive balance mechanisms, and visual novelty should be prioritized (Bachman et al., 2012; Vessel & Russo, 2015), e.g., a dynamic VR environment. These HSI technologies with diverse sensory input are especially important to investigate as they may also aid in the continued CBS treatment/intervention of those who develop spaceflight associated neuro-optical syndrome (SANS) (McGregor et al., 2021). HSIA research should ask how HSI technologies can monitor and support social cohesion within the crew, especially in the case of crews with diverse racial/ethnic, gender, and cultural backgrounds. Wearable HSI technologies, for example, may allow tracking of social behavior and interaction patterns to assess affective states (Zhang et al., 2018). For all HSI countermeasures, outcome measurements (such as biomarkers and performance metrics) must be established to understand efficacy and extent of accepted risk (Basner, 2015; Moore et al., 2015; NASA HRP Communications, 2019a, Vessel, 2015).

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