

# Neurological and Neurobehavioral Risks of Living in Space: A Policy Framework for Sustainable Human Settlement Beyond Earth

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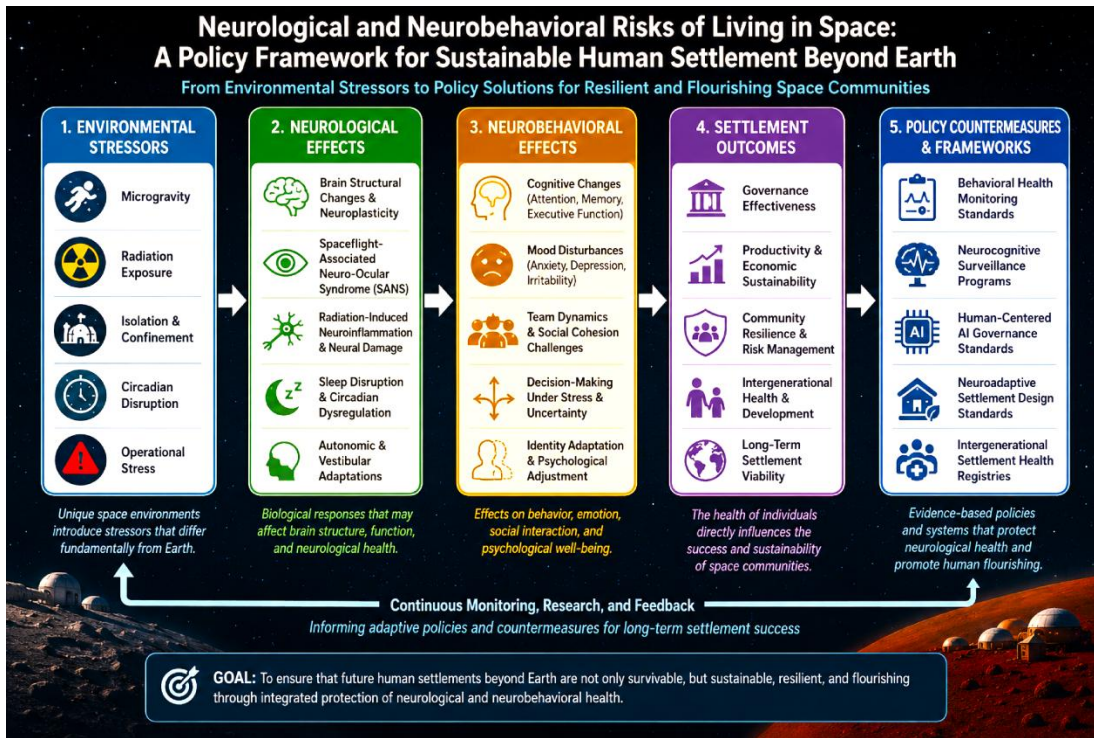
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## Abstract

Humanity is approaching a historic transition from short-duration space exploration to the establishment of permanent communities beyond Earth and entering an era in which permanent habitation beyond Earth is transitioning from aspiration to emerging reality. Planned lunar settlements, commercial space stations, and future Martian communities will expose humans to environmental conditions fundamentally different from those under which the human brain evolved. While engineering systems, propulsion technologies, radiation protection, and life-support infrastructure have received significant attention, comparatively less focus has been directed toward the neurological and neurobehavioral consequences of living in space over extended periods. Evidence from neuroscience, psychology, human spaceflight, and terrestrial analog environments suggests that microgravity, radiation exposure, isolation, confinement, circadian disruption, and operational stress may influence cognition, emotional regulation, decision-making, social cohesion, and mental health. These effects have implications not only for individual astronauts but also for governance, community resilience, economic productivity, and the long-term sustainability of extraterrestrial settlements. This paper reviews key neurological and neurobehavioral risks associated with living in space and proposes policy recommendations for future settlements. It argues that neurological and behavioral health should be viewed not merely as medical concerns but as strategic settlement resources essential to the creation of resilient, adaptive, and flourishing spacefaring communities.

**Keywords:** space settlement, neuroscience, behavioral health, human performance, space policy, analog astronautics, artificial intelligence, human flourishing



## 1. Introduction

Humanity stands at the threshold of becoming a multi-planetary species. Government space agencies, commercial enterprises, and international partnerships are actively developing lunar habitats, commercial space stations, and architectures for eventual human settlement of Mars. Historically, human spaceflight has focused on exploration missions measured in days, weeks, or months. Permanent settlement introduces a fundamentally different challenge. Future inhabitants of extraterrestrial communities will not simply be astronauts completing missions and returning home. They will be residents, workers, educators, healthcare professionals, caregivers, leaders, and eventually families raising future generations beyond Earth. The human brain evolved under conditions unique to Earth. Gravity, atmospheric composition, circadian rhythms, biodiversity, sensory diversity, and complex social structures have shaped human neurological and psychological development over millions of years. Space environments alter many of these conditions simultaneously. Understanding the consequences of these changes represents one of the most important challenges facing future settlement planners. Research from neuroscience, behavioral health, and human spaceflight suggests that prolonged exposure to space environments may influence cognition, emotional regulation, interpersonal relationships, and decision-making (Pagel & Choukèr, 2016; Roberts et al., 2017). At the same time, scholars examining the psychology of space migration emphasize that future success depends not only on maintaining health but on creating conditions that support adaptation, resilience, and thriving beyond Earth (Nezami et al., 2022). The central policy question facing future settlement planners is therefore not simply whether humans can survive in space, but whether humans can build sustainable and flourishing communities there.

## 2. Neurological Risks of Living in Space

### 2.1 Brain Structural Changes and Neuroplasticity

Recent neuroimaging studies have demonstrated measurable changes in astronaut brain structure following long-duration spaceflight. These include ventricular enlargement, redistribution of cerebrospinal fluid, and alterations in sensorimotor brain regions associated with adaptation to microgravity (Koppelmans et al., 2016; Roberts et al., 2017; McGregor et al., 2023). These findings suggest that the human brain exhibits remarkable neuroplasticity when adapting to altered gravitational environments. While many observed changes appear adaptive, important questions remain regarding cumulative exposure and long-term neurological consequences. Future settlers may spend years or decades in reduced-gravity environments, creating circumstances that have never existed in human history. Researchers remain uncertain whether prolonged exposure to reduced gravity may influence executive functioning, memory, attention, emotional regulation, or cognitive aging. These questions become particularly important when considering permanent settlements where individuals must participate in governance, education, healthcare, and community leadership.

## **2.2 Spaceflight Associated Neuro-Ocular Syndrome**

Spaceflight-associated neuro-ocular syndrome (SANS) has emerged as a significant concern during long-duration missions. Structural changes involving the eye and optic nerve have been documented among astronauts exposed to microgravity for extended periods. Prolonged exposure to microgravity has been associated with optic disc edema, globe flattening, choroidal folds, hyperopic refractive shifts, and other neuro-ophthalmologic findings that may affect visual performance and operational capability (Lee et al., 2020). Although the underlying mechanisms remain under investigation, fluid redistribution and altered intracranial dynamics are believed to contribute to these effects. Future settlements may therefore require routine neurological and ophthalmological monitoring programs as components of long-term public health systems.

## **2.3 Space Radiation and Neural Health**

Radiation exposure remains one of the most significant biological challenges associated with deep-space habitation. Earth's magnetic field and atmosphere provide substantial protection against galactic cosmic radiation and solar particle events. Extraterrestrial settlements will not benefit from these natural defenses to the same degree. Experimental studies suggest that chronic radiation exposure may influence neuroinflammation, neuronal signaling, cognitive performance, and neurodegenerative processes (Davis et al., 2021; Kokhan et al., 2023). Although engineering countermeasures such as shielding and underground habitats may reduce exposure, the long-term neurological consequences of multi-decade residence beyond Earth remain uncertain. The implications extend beyond individual health. Neurological impairment affecting judgment, cognition, or decision-making could influence the stability and resilience of entire communities.

## **2.4 Sleep and Circadian Disruption**

Human neurological functioning is closely linked to circadian rhythms synchronized to Earth's twenty-four-hour cycle. Spaceflight environments frequently disrupt these rhythms through altered light exposure, operational demands, and artificial habitat conditions. Sleep disruption has been associated with impaired attention, slower reaction times, mood disturbances, and decreased cognitive performance. Chronic sleep deficiency may affect educational achievement, occupational performance, interpersonal relationships, and emotional well-being. Future settlements should therefore treat sleep and circadian health as critical components of public health infrastructure rather than merely personal wellness concerns.

# **3. Neurobehavioral Risks and Human Performance**

### **3.1. Isolation and Confinement**

Isolation and confinement represent some of the most extensively studied psychosocial stressors associated with spaceflight. Similar conditions have been investigated in Antarctic stations, submarines, underwater habitats, and analog astronaut environments. Observed outcomes include loneliness, depression, anxiety, reduced motivation, interpersonal conflict, and social withdrawal (Pagel & Choukèr, 2016). The Mars500 study demonstrated that prolonged confinement can influence mood, cognitive performance, and crew dynamics, emphasizing the importance of behavioral health support systems (Basner et al., 2014). Future settlements may amplify these challenges because residents will not simply complete missions and return home. For many individuals, the settlement itself may become home.

### **3.2 Communication Delays and Social Separation**

Future Martian communities may experience communication delays ranging from several minutes to more than twenty minutes each way. These delays fundamentally alter social relationships with Earth. Residents may experience increased psychological distance from family members, cultural institutions, and support networks. Over time, such conditions may contribute to the emergence of distinct social identities and cultural norms. Understanding the psychological consequences of these changes will be critical for future settlement planning.

### **3.3 Family Systems and Community Development**

Most space psychology research has focused on highly selected astronaut populations. Future settlements will eventually include children, families, educators, healthcare providers, and aging populations. This transition introduces challenges that extend beyond traditional mission psychology. Communities must support childhood development, education, family relationships, social institutions, and intergenerational continuity. Consequently, future research must expand beyond astronaut psychology and increasingly incorporate perspectives from community psychology, sociology, and public health.

## **4. Psychological Adaptation and Identity**

### **4.1 Human-AI Teaming and Behavioral Health and Ops**

Artificial intelligence is expected to become deeply integrated into future settlements. AI systems may support healthcare, education, environmental management, behavioral health services, and operational decision-making. Such systems offer substantial opportunities. They may provide continuous support in environments where human specialists are limited or unavailable. They may assist with behavioral health monitoring, educational support, and personalized interventions. However, increasing reliance on AI also introduces important challenges. Questions regarding transparency, trust, accountability, autonomy, and cognitive dependence remain unresolved. Emerging frameworks such as the Multi-Agent AI Governance System for Behavioral Health and Operations (MAGSBHO) have proposed governance-constrained approaches to integrating behavioral health support, virtual psychiatry, and operational assistance within human-in-command architectures (Jewell, 2026b). Such approaches may provide valuable models for future settlements where communication delays limit real-time support from Earth. The objective should not be replacing human judgment but augmenting human capability while preserving autonomy and accountability.

### **4.2 Longitudinal Monitoring and Preventive Countermeasures**

One of the greatest limitations in current space medicine is the relatively small number of individuals exposed to long-duration spaceflight. Understanding adaptation across years or decades requires new approaches to longitudinal monitoring and data collection. Future settlement health systems may need to integrate physiological, neurological, psychological, behavioral, and environmental data into comprehensive monitoring frameworks. Such systems could support earlier identification of emerging risks and more personalized preventative interventions. The Analog Astronaut OMICS Library Project (AAOLP) represents one example of an effort to establish longitudinal biopsychosocial datasets capable of supporting future space medicine research and preventative countermeasure development (Jewell, 2026a). Analog astronaut programs provide opportunities to evaluate physiological adaptation, behavioral health, team dynamics, and preventative interventions before large-scale settlement occurs. These environments may serve as important translational bridges between terrestrial research and future extraterrestrial communities.

## **5. Neurological and Neurobehavioral Health as a Strategic Settlement Resource**

Historically, space exploration has treated human health primarily as an operational requirement. The objective has been to maintain astronaut performance sufficiently to accomplish mission goals and ensure safe return to Earth. Permanent settlement fundamentally changes this paradigm. Future settlements will not simply be exploration platforms. They will be communities. Their long-term success will depend upon their ability to maintain social stability, effective governance, educational systems, economic productivity, cultural development, and intergenerational continuity. Each of these outcomes is directly influenced by neurological and neurobehavioral health. A settlement experiencing widespread sleep disruption, chronic stress, social fragmentation, cognitive decline, or behavioral health challenges may remain technically operational while becoming socially fragile. Conversely, communities that support resilience, cooperation, adaptive decision-making, and psychological well-being may be better positioned to withstand environmental, operational, and societal stressors. This perspective suggests that neurological and neurobehavioral health should be viewed not merely as medical concerns but as strategic settlement resources. Just as future settlements will manage water, energy, food, and environmental systems, they may also need to actively manage conditions that support cognitive functioning, emotional well-being, and social cohesion.

### **5.1 Human Flourishing as a Settlement Objective**

Much of the current space medicine literature appropriately focuses on preventing disease, mitigating risk, and preserving operational performance. However, a civilization cannot be built upon risk mitigation alone. Long-term settlement requires a positive vision of what constitutes a successful human community. Individuals require opportunities for meaning, belonging, learning, creativity, exploration, and contribution. Communities require shared values, cultural development, educational institutions, and systems that encourage cooperation and stewardship. Throughout history, societies have demonstrated that prosperity alone does not guarantee well-being. Communities flourish when individuals perceive purpose in their lives, feel connected to others, and participate in activities that contribute to something larger than themselves. Future settlements should therefore be evaluated not only according to engineering metrics or economic productivity but also according to measures of human well-being, social cohesion, educational opportunity, and psychological resilience. The long-term success of humanity beyond Earth may ultimately depend upon our ability to create environments that support both technological advancement and human development.

## **6. Policy Implementation Framework**

The transition from exploration missions to permanent settlements will require a corresponding transition in policy development. Existing space medicine frameworks are largely designed to

support astronaut performance during finite missions. Settlement policies must instead support communities across decades and generations.

## **6.1 Future Research Priorities**

Significant knowledge gaps remain regarding the long-term neurological and neurobehavioral consequences of living beyond Earth. While current evidence provides important insights, most available data originates from relatively small astronaut populations, short-duration missions, or terrestrial analog environments. Future research should prioritize longitudinal studies of reduced-gravity adaptation, radiation-related neurological risks, family systems in extraterrestrial environments, human-AI teaming, and multi-generational settlement development. Expanded analog astronaut research programs and longitudinal initiatives such as AAOLP may help bridge critical knowledge gaps before large-scale settlement occurs.

## **6.2 Policy Recommendation**

### **6.2.1 Policy Recommendation 1: Behavioral Health Monitoring Standards**

Future space settlements should establish standardized behavioral health monitoring frameworks comparable to existing occupational health and public health surveillance systems on Earth. Behavioral health assessments should move beyond episodic screening and become integrated components of routine settlement operations. Monitoring programs should include validated measures of mood, stress, sleep quality, fatigue, social connectedness, team cohesion, workload, psychological resilience, and overall well-being. Digital phenotyping technologies, wearable biosensors, and confidential self-report systems may provide opportunities for continuous monitoring while preserving privacy and autonomy. Participation in monitoring programs should be guided by informed consent, transparency, privacy protections, and clearly defined limitations regarding data access, storage, and use. The primary objective of behavioral monitoring should be early identification of support needs and preventative interventions rather than surveillance or performance evaluation. International standards developed through collaboration among governmental agencies, commercial operators, academic institutions, and international organizations could facilitate consistent data collection and evidence-based intervention strategies across diverse settlement environments.

### **6.2.2 Policy Recommendation 2: Neurocognitive Monitoring Programs**

Long-duration residence in reduced-gravity and radiation-exposed environments may affect cognitive performance, decision-making, executive functioning, attention, memory, and neurobehavioral adaptation. Future settlements should therefore implement longitudinal neurocognitive monitoring programs designed to identify emerging changes before they affect operational performance, public safety, or quality of life. Routine assessments may include measures of attention, memory, executive function, spatial orientation, reaction time, cognitive workload, and decision-making capacity. These evaluations should be integrated into long-term public health systems rather than restricted to astronaut selection and mission operations. The objective is not to identify failure but to support adaptation. Early detection of neurological changes may enable timely interventions, personalized countermeasures, and improved understanding of human adaptation to extraterrestrial environments. Neurocognitive monitoring should be used to support preventative healthcare and adaptive performance rather than serve as a mechanism for employment screening, social control, discrimination, or exclusion. Policies should ensure that neurological data are protected under the same ethical standards applied to other sensitive health information.

### **6.2.3 Policy Recommendation 3: Human-Centered AI Governance Standards**

Artificial intelligence will likely become an essential component of future settlement infrastructure, supporting healthcare, education, environmental management, logistics, behavioral health services, and operational decision-making. As reliance on AI increases, governance frameworks must ensure that these systems remain transparent, accountable, and aligned with human values. Future policies should require human-in-command architecture for critical health, behavioral, and operational decisions. AI systems should augment rather than replace human judgment. Standards should address explainability, privacy protection, algorithmic bias, cybersecurity, data governance, and mechanisms for meaningful human oversight. Behavioral health applications warrant particular attention because they involve sensitive psychological information and may influence personal decision-making. Governance frameworks should preserve individual autonomy while ensuring appropriate safeguards against misuse, manipulation, or excessive dependence upon automated systems. Future settlements should adopt the principle that responsibility for consequential decisions affecting human health, safety, rights, or governance must remain attributable to identifiable human decision-makers. Accountability should never be delegated entirely to autonomous systems.

#### **6.2.4 Policy Recommendation 4: Neuroadaptive Settlement Design Standards**

The design of future habitats should recognize that physical environments directly influence neurological and psychological well-being. Settlement architecture should therefore be informed not only by engineering requirements but also by principles derived from neuroscience, environmental psychology, architecture, and human factors research. Design considerations should include circadian lighting systems, access to private and communal spaces, acoustic management, biophilic elements, visual variability, opportunities for physical activity, naturalistic environmental cues, and environments that support social interaction and cognitive restoration. Long-duration habitation in highly artificial environments may contribute to psychological fatigue, social stress, and reduced well-being. Neuroadaptive design principles can help mitigate these risks by creating environments that support cognitive health, emotional resilience, and social cohesion. Future settlements should be evaluated not only for engineering performance and operational efficiency but also for their capacity to support psychological well-being, social connectedness, and long-term human flourishing.

#### **6.2.5 Policy Recommendation 5: Intergenerational Settlement Health Registries**

Future settlements may eventually include individuals who spend their entire lives beyond Earth and potentially children born in extraterrestrial environments. Understanding the long-term neurological, physiological, psychological, developmental, and social effects of such conditions will require longitudinal data collection across generations. Internationally coordinated settlement health registries should be established to monitor developmental, neurological, cognitive, behavioral, and public health outcomes over time. Such registries would provide critical evidence for evaluating adaptation to reduced gravity, radiation exposure, altered ecosystems, evolving settlement cultures, and intergenerational human development beyond Earth. Participation in such registries should remain voluntary whenever feasible and should operate under internationally recognized ethical standards for human subjects research, medical privacy, and public health data governance. Appropriate safeguards, transparency mechanisms, and informed consent procedures must be incorporated from the outset. International collaboration should be encouraged to ensure interoperability of settlement health datasets across governmental, commercial, academic, and multinational settlement programs. The resulting datasets may become one of the most valuable scientific resources for understanding the future of human life beyond Earth and informing evidence-based settlement policy.

### **7. Policy Synthesis**

Collectively, these recommendations recognize that neurological and neurobehavioral health are not merely medical concerns but foundational elements of settlement resilience. Just as future space communities will invest in life-support systems, energy infrastructure, environmental protection, and resource management, they must also invest in the cognitive, psychological, and social systems that enable individuals and communities to thrive. The long-term success of human settlement beyond Earth may depend as much on these human-centered policies as on any technological advancement. Sustainable settlements will require not only engineering excellence but also governance frameworks that protect human dignity, support adaptation, promote resilience, and foster the conditions necessary for future generations to flourish.

## 8. Conclusion

The future of space settlement will ultimately depend upon more than engineering success. It will depend upon humanity's ability to create environments that preserve cognitive capacity, psychological resilience, social cohesion, and opportunities for meaningful lives. Throughout history, civilizations have risen or declined not solely because of technological capability, but because of their ability to sustain healthy, adaptive, and cooperative communities. The same principle is likely to apply beyond Earth. As humanity prepares to establish permanent communities on the Moon, Mars, and beyond, neurological and neurobehavioral health should be recognized as foundational components of settlement planning. The challenge before us is not merely to survive in space, but to create the conditions under which future generations can flourish there. The success of a spacefaring civilization may ultimately be measured not by how far humanity travels, but by how well it preserves the neurological, psychological, and social foundations of what makes us human.

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