Sensory-Motor Adaptation to Space Flight: Human Balance Control and Artificial Gravity

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Gravity, which is sensed directly by the otolith organs and indirectly by proprioceptors and exteroceptors, provides the CNS a fundamental reference for estimating spatial orientation and coordinating movements in the terrestrial environment. The sustained absence of gravity during orbital space flight creates a unique environment that cannot be reproduced on Earth. Loss of this fundamental CNS reference upon insertion into orbit triggers neuro-adaptive processes that optimize performance for the microgravity environment, while its reintroduction upon return to Earth triggers neuro-adaptive processes that return performance to terrestrial norms.

Five pioneering symposia on The Role of the Vestibular Organs in the Exploration of Space were convened between 1965 and 1970. These innovative meetings brought together the top physicians, physiologists, and engineers in the vestibular field to discuss and debate the challenges associated with human vestibular system adaptation to the then novel environment of space flight. These highly successful symposia addressed the perplexing problem of how to understand and ameliorate the adverse physiological effects on humans resulting from the reduction of gravitational stimulation of the vestibular receptors in space. The series resumed in 2002 with the Sixth Symposium, which focused on the microgravity environment as an essential tool for the study of fundamental vestibular functions. The three day meeting included presentations on historical perspectives, vestibular neurobiology, neurophysiology, neuroanatomy, neurotransmitter systems, theoretical considerations, spatial orientation, psychophysics, motor integration, adaptation, autonomic function, space motion sickness, clinical issues, countermeasures, and rehabilitation. Scientists and clinicians entered into lively exchanges on how to design and perform mutually productive research and countermeasure development projects in the future. The problems posed by long duration missions dominated these discussions and were driven by the paucity of data available. These issues along with more specific recommendations arising from the above discussions will be addressed an upcoming issue of the Journal of Vestibular Research.

Postflight balance control deficits resulting from sensory-motor adaptive responses to the microgravity environment were recognized early on as a potential untoward side effect of orbital space flight. During the First Symposium in 1965, Graybiel and Fregly introduced a "Quantitative Ataxia Test Battery," which was subsequently used to demonstrate balance control deficits in crewmembers returning from orbital missions in the late 1960s and early 1970s. During the Third Symposium in 1967, TDM Roberts introduced the concept of a labyrinthine-generated "behavioral vertical" to explain a critical role the vestibular apparatus plays in providing a dynamic internal reference frame for neuro-motor control of upright stance, and during the Fourth Symposium in 1968 a number of investigators presented data demonstrating the confluence of multi-sensory information in the vestibular nuclei and the cerebellum and detailed anatomical and physiological descriptions of the vestibulo-spinal system. Throughout the series evidence was also provided for adaptive plasticity in sensory-motor function.

Since those days our understanding of terrestrial balance control has progressed rapidly. In parallel, numerous space flight investigators have contributed to our understanding of the characteristics, demographics, and mechanisms underlying the transient loss of balance control following space flight. Human studies of integrated balance control performance, neuro-motor reflex function, proprioceptive function, and visual-perceptive function have been performed on U.S. and Russian Missions since the 1960s. Animal studies of remodeling in the cerebellum and vestibular end organs have also been performed in both programs.

Postflight decrements in sensory-motor control have now been well characterized from both basic science and occupational health perspectives. Early after flight postural stability is disrupted in all crewmembers. During short duration missions the underlying cause appears to be vestibular system adaptation, but as mission duration increases somatosensory/motor control system adaptation begins to play an important role. The mechanisms of this slower phase of in-flight adaptation are not yet well understood, but understanding them may be critical to the success of extended duration missions beyond low Earth orbit. As mission duration increases there is also an increased incidence of postflight autonomic dysfunction. For example, orthostatic hypotension, which can exacerbate the balance control deficits, may result in part from vestibular autonomic system alterations.

Owing to the untoward effects of these adaptive responses on astronaut performance, their behavioral manifestations have been fairly well characterized; however, the anatomical sites involved and neurological mechanisms responsible have not. Understanding the cellular and molecular bases for these adaptive responses may be among the greatest challenges of modern neuroscience (Pompeiano, 2002), but the payoff may be improved quality of life for aging individuals, improved therapies for spinal cord injuries and vestibular disorders, improved techniques for rehabilitation from sensory-motor injuries, improved training for elite athletes, and safe extension of both time and distance for human space exploration. Recent results from investigations aboard the space shuttle have begun to identify both sites and mechanisms of vestibular system adaptation, and have demonstrated the feasibility of using orbiting laboratories to investigate the fundamental role that gravity plays in neurological processes. Future laboratory capabilities aboard the International Space Station should expand the role of space flight in exploring fundamental questions in neurophysiology, and these answers, in turn, should reduce the limitations of neurophysiology on space exploration.

To facilitate the next steps in human exploration of space, the mechanisms of somatosensory adaptation and the interactions between vestibular adaptation and altered autonomic system function must be more fully understood. Ground-based venues are unlikely to serve as adequate analogs for these investigations, so space flight venues will be required. Also should the functional implications of these long-duration adaptive responses present sufficient risk to the success of future missions, adequate countermeasures must be developed. This too will require space-based experiment platforms, possibly including animal and human centrifuges to provide artificial gravity.

As NASA prepares for unprecedented human missions to the Moon and Mars, the neuro-vestibular/sensory-motor community will face unprecedented challenges in protecting the health, safety, and performance of the crews aboard these missions. Data from six-month low Earth orbit space flight missions suggest that that substantial neuro-vestibular/sensory-motor adaptation will take place during six-month transit missions to and from Mars. Could intermittent or continuous artificial gravity be used to offset these effects? To what degree would the effects of adaptation to this rotational cure affect its potential benefits? Also, little information exists regarding the gravity thresholds for maintaining functional performance of complex sensory-motor tasks such as balance control and locomotion. Will sensory-motor coordination systems adapt to 30-90 days of 1/6 g on the lunar surface or 18 months of 3/8 g on the Martian surface? Would some form of gravity replacement therapy be required on the surface? And, will transitions between 0 g and 1/6 g or 1/3 g present as great a challenge to the vestibular system as transitions between 0 g and 1 g? Answers to these and other related questions will require concerted research and development efforts, the results of which will lead not only to operational countermeasures, but also to an improved understanding of the role that gravity plays in spatial orientation and movement control, and likely to an improved understanding of the stimuli and mechanisms of adaptive neural processes at least in sensory-motor coordination and control.