Journal of Vestibular Research 11 (2001/2002) 311-340
IOS Press

Abstracts: 6th NASA Symposium on The Role of the Vestibular Organs in the Exploration of Space

N1.1

Micro-gravity and artificial gravity: Two challenges to neuro-vestibular adaptation

Laurence R. Young
Man-Vehicle Laboratory, Department of Aeronautics and Astronautics, MIT, Cambridge, MA

Among the most intriguing characteristics of the vestibular system is its ability to adapt to altered environments. To an engineer originally interested in automatic control, guidance, and navigation, the versatility and rapidity of neuro-vestibular adaptation has been nothing short of amazing. Dancers and pilots appropriately shorten their post rotatory nystagmus and motion sensation. Sailors adapt to the frequency of their own ship's motion, only to experience motion sickness in another boat or on the dock. The ability of patients to recover from hemi-labyrinthectomy as well as the use of neck reflexes to augment vestibular responses represents only a beginning of adaptation. Modification of the gain, the phase, and even the direction of the vestibulo-ocular reflex according to the requirements for visual stabilization is a further marvel. The discovery of context-specific adaptation of the VOR, first noted with magnifying spectacles and then with bifocals is another watershed. And, more recently, with exposure of astronauts to weightlessness and to the return to earth we have seen a measure of adaptation in which the end organ remains intact but the geometric meaning of its signals requires reinterpretation. Finally, renewed interest in short radius centrifugation for artificial gravity has stimulated research into the nature and effectiveness of multiple program adaptation to several vastly differing gravito-inertial environments. Satisfactory astronaut adaptation will be required for multiple environments: spinning, weightlessness, terrestrial and Martian gravity. Progress and open issues for models and experiments will be presented.

N1.2

The role of NASA in the exploration of the vestibular organs

F.E. Guedry, Jr.
Institute for Human and Machine Cognition, University of West Florida, Pensacola, FL

Teams of engineers, physicists, and a broad spectrum of scientists and technicians, all focused on putting astronauts into orbit around the Earth and Moon, were assembled and supported by NASA . The remarkable interdisciplinary synergy that developed yielded success in both goals, and a tremendous technology spin-off for the entire world. Of course the primary reason for the entire enterprise was the exploration of the vestibular organs, which have always intrigued physicists and engineers because the vestibular system consists of two sets of tri-axial angular and linear accelerometers. Engineers and physicists, realizing that the response of these sensors could be predicted if the value of several parameters were known, wanted to explore responses in the frequency domain. The semicircular canals are Œon1 angular velocity in the frequency range of most head movements, and the otolith organs are Œon1 head-tilt position during low frequency head movements, and Œon1 head linear velocity, during high frequency (i.e., change in linear acceleration) head movements. Because Titov, a Cosmonaut, experienced motion sickness when he moved his head on orbit, the price of vestibular stock went up. Biomedical scientists began studying adaptation to strange environments such as rotating space stations, and their counterpart, weightlessness, motion sickness was again studied intensively. As a result, diagnosis and rehabilitation of dizzy patients has improved, and procedures were developed to help airsick pilots overcome the problem. Through interactions with engineers, physicists, physicians, and neuro-scientists in NASA-sponsored meetings, I learned that Spatial Orientation is much more than setting a line to vertical and signaling cessation of rotation. These meetings changed my way of thinking about spatial orientation, and they precipitated a worldwide influx of graduate students in Universities. NASA supported research on adaptation to continuous rotation (Slow Rotation Room), Translation-VOR during linear oscillation and during centrifugation, Dynamic Visual Acuity (DVA). Some new data on TVOR and DVA will be described along with a few personal experiences in my adventures in Aerospace research.

N1.3

A historical review of vestibular and sensory-motor research in space flight

Millard F. Reschke
Neurosensory Laboratories, Johnson Space Center, Houston, TX

Whether the dawn of space flight began with primitive man gazing upon the heavens or with the fatal flight of Icarus, we know that modern man predicted our escape from Earth's atmosphere as early as 1911 when Tsiolkovsky noted in a letter to a friend that "Humanity will not

0957-4271/01/02/$8.00

remain on the Earth forever, but in the pursuit of light and space will at first timidly penetrate beyond the limits of the atmosphere, and then will conquer all the space around the Sun." Historically, modern space flight began in the fifth decade of the twentieth century, and owes its success to the mythology of Daedalus and Icarus, the physics of Archimedes, Newton, Galileo, and Copernicus, the foresight of DaVinci, Jules Verne and H.G. Wells, the vision of Tsiolkovsky, Oberth, Von Braun, Korolev, and the daring of Yuri Gagarin and Alan Shepard.

Those familiar with the initial plans to rocket a man into space will recall that flight surgeons expressed concern that the body organs depended on sustained gravity and would not function in space. Others worried over the combined effects of acceleration, weightlessness, and the heavy deceleration during atmospheric entry. Still other experts were concerned especially about perception and vestibular function. Heinz Haber and Otto Gauer, speculated that the brain receives signals on the position, direction, and support of the body from four mechanisms: pressure on the nerves and organs, muscle, posture, and the vestibular organs. Modification of anyone of these inputs, they theorized, would disrupt normal functioning of the autonomic nervous system with the ultimate inability to act. Fortunately, the human nervous system has proven to be enormously plastic.

Not including the daring flights of the X-15, Russia and the United States have recently completed a combined total of 236 manned space flights. The majority of these flights, although not always in a formal sense, have involved questions of sensory-motor, and vestibular function. Most individuals concerned with space physiology are familiar with publicized flights that involved either sensory-motor or neurovesitbular function: Skylab 2-4, the first Spacelab flight (SL-1), the first German Spacelab flight (D-1), the first International Microgravity Laboratory flight (IML-1), the first dedicated Life Sciences Spacelab flight (SLS-1), and the first Neurolab Spacelab. However, most are not familiar with the 34 Extended Duration Orbiter Medical Program (EDOMP) shuttle flights where beginning with STS-28 and ending with STS-72 detailed neurosensory investigations were conducted. Fragments of the EDOMP science were carried over onto the long duration cooperative MIR flights between the United States and Russians. This paper will trace the development of sensory-motor and vestibular investigations across flights beginning with the daring flight of Gagarin aboard Vostok-1 to the present. The intention and purpose of this historical approach is to first provide researchers with a single, common reference document, and secondly to allow those who helped create this history a record of accomplishment.

N1.4

Ashton Graybiel's Contributions To Our Knowledge of Spatial Orientation

James R. Lackner
Ashton Graybiel Spatial Orientation Laboratory, Brandeis University, Waltham, MA

Ashton Graybiel made systematic contributions to nearly all aspects of human orientation and movement control in aerospace environments over the course of nearly 50 years. This was actually his second career. His earlier work had concerned electrocardiography, a field in which he was also a pioneer. The present paper reviews selected aspects of his contributions to our knowledge of human orientation and sensory localization beginning with his early studies of the audiogyral and oculogyral illusions and ending with his studies of head movement control in weightless and high force environments. His work on adaptation to artificial gravity environments will also be briefly considered.

N2.1

The role of space in the exploration of vestibular organs

Muriel D. Ross
University of New Mexico Health Sciences Center, Albuquerque, NM

When the series of symposia on "The Role of the Vestibular Organs in Space Exploration" began, it was believed that the vestibular organs would prove to be the Achilles heel of space exploration because astronauts would be too ill to carry out missions. Instead, space has proven to be relatively benign. The human organism has shown a remarkable ability to adapt to reduced gravity. Here, the focus is instead on the role of space in the exploration of the vestibular organs. In untreated astronauts, the vestibular response to weightlessness is immediate, with symptoms lingering for from a few to several days. This situation reverses upon return to Earth, with some symptoms prolonged after long-term flight. Relevant studies of rat models exposed to weightlessness for 9-16 days demonstrate that the utricular portion of the vestibular system begins adaptation to weightlessness rapidly. Synaptic increments occur in hair cells by day 2 inflight (FD2) and by FD13-14 are significant only in type II cells. Reversal has begun within 4.5-6 hrs after return to Earth. These results showing synaptic adaptation to weightlessness and readaptation to Earth's 1g postflight correspond well with physiological responses recorded in Opsanus tau (Boyle et al, J Neurophysiol 86:2118-2122). However, in rat saccular macula, synapses in type I cells show a significant decline by FD2 ($p \geq 0.0105$), return to near control levels on FD14 and undergo a second significant decline postflight (PFD2) ($p \geq 0.0182$). No later postflight saccular synapse data are yet available, nor are there physiological correlates for the anatomical data. The conclusion is that hair cells and the two maculae respond differently to weightlessness. How is this related to physiological differences? Can the saccular changes alone explain prolonged readaptation to Earth's 1g? Further results also indicate that maculae process information in parallel and have local feedback circuits that doubtless are tied to synaptic plasticity. However, we are far from comprehending either the fundamental or the clinical implications of this circuitry. Space research is essential to attain better understanding using integrated anatomical, physiological and neurochemical approaches. There should be better integration between human and animal investigations for correlations. Additionally, we desperately need the Space Station centrifuge to provide true controls for the effects of weightlessness on humans and on animal models, and to learn the partial gravity level necessary for adaptive responses to occur in anticipation of Mars. Renewed commitment can fulfill the exceptional promise space research offers in understanding vestibular organs to benefit space exploration and clinical treatment on Earth. (This research was supported by a NASA and by Grant #47305 from the National Institute of Mental Health.)

N2.2

Alterations in the ultrastructure of adult rat cerebellar nodulus during adaptation to spaceflight and re-adaptation to earth

G.R. Holstein, G.P. Martinelli
[1]*Department of Neurology, Mount Sinai School of Medicine, New York, NY*

Alterations in sensory and motor function occur during and following exposure to microgravity. Vestibular abnormalities may include postural illusions, sensations of rotation, nystagmus, dizziness, and vertigo. Adaptation to the microgravity environment usually occurs within one week, and a subsequent re-adaptation period is often required upon return to Earth. During this re-adaptation period, recurrences of dizziness, nausea and vomiting, and disturbances in postural equilibrium in the absence of vision may occur. The present study was conducted to identify the ultrastructural alterations in adult rat cerebellar cortex that correlate with short-term adaptation to spaceflight and re-adaptation to Earth. Hindbrain tissue was obtained from adult rats flown on the Neurolab shuttle mission (STS-90) as part of an IACUC-approved experiment. Tissue for the present report was obtained from four rats sacrificed on orbit during flight day 2 (FD2) and five animals sacrificed on Earth 24 hr after shuttle return (R+1). Following decapitation, hindbrains were immersion-fixed in aldehydes for 18 days, and then the cerebellum was dissected away from the ventral portion of the brainstem by severing the cerebellar peduncles. The entire cerebellum of each rat was Vibratome-sectioned parasagittally. These sections were collected serially, processed for electron microscopy, and embedded as tissue wafers in resin. Complete reconstructions of the nodulus from each animal were performed and used to identify the midsagittal tissue wafer. Using this as the zero point, the wafers from the otolith-recipient parasagittal zones were identified and examined using electron microscopy. Cisterns of smooth endoplasmic reticulum that are normally present in Purkinje cells were substantially enlarged in tissue from the nodulus of FD2 and R+1 flight animals. The increased complexity of these cisterns resulted in the formation of lamellar bodies that were observed throughout entire Purkinje cells, including the somata, dendrites, thorns, and axon terminals. Profoundly enlarged mitochondria were also apparent in some nodular Purkinje cells from FD2 and R+1 animals, as well as electron-dense degeneration in Purkinje cell dendrites. The latter profiles contained increased numbers of lysosomses and degenerated mitochondria, but maintained apparently healthy synaptic contacts with normal-appearing axon terminals. In addition to degeneration of postsynaptic elements, evidence of a separate process of synaptic remodeling was obtained. Parallel fiber-Purkinje cell synapses involved in this process were characterized by retraction of the synaptic vesicles away from the region of membrane contact. These morphologic findings were not apparent in control animals or tissues. The present results provide ultrastructural evidence for neuronal and synaptic plasticity in the nodulus of adult rats during early adaptation to, and re-adaptation following spaceflight. The particular nature of the structural alterations, including the formation of lamellar bodies and the presence of degeneration, further suggests that excitotoxity may play a role in the short-term neural response to spaceflight. (Supported by NASA grant NAG2-946 and NIH grant DC02451 from the NIDCD)

N2.3

Effects of 2G exposure on c-Fos expression in the *het* mouse hypothalamus

Charles A. Fuller
Section of Neurobiology, Physiology & Behavior, University of California, Davis, CA

Exposure to altered force environments has profound affects on physiological homeostasis. Utilizing the head-tilt (*het*) mouse model, we previously demonstrated a novel role for the vestibular system, specifically the maculae organs, in transducing the ambient force environment (+G) and largely mediating the acute feeding, body mass, body temperature and circadian rhythms response to +G. Because the neuronal circuits responsible for feeding, thermal balance and circadian rhythm genesis are located, to a large extent, in the hypothalamus, the highly attenuated physiological responses of the *het* mice suggest a vestibulo-hypothalamic connection. To further explore this putative relationship, we exposed 6 adult *het* and 6 age-matched wildtype littermate mice to 2G for 2 hours and compared the c-Fos response to 1G controls. Following 2G exposure, the mice were trans-cardially perfused with saline followed by 4% paraformaldehyde. The brains were then removed and immunohistochemically processed for c-Fos expression in specific hypothalamic nuclei. Compared to 1G controls, the wildtype exhibited robust c-Fos expression in all hypothalamic nuclei evaluated. These include the suprachiasmatic, arcuate, paraventricular, lateral, dorsal, ventromedial and tuberomamillary nuclei. In contrast to the 2G wildtypes, the *het* mice exposed to 2G exhibited little to null c-Fos expression in any of the hypothalamic nuclei. These findings further support the contention that a vestibulo-hypothalamic linkage does exist and is likely a neuronal substrate for the physiological sequelæ of vestibular dysfunction.

N2.5

The many facets of the otolith – a review

Andrew H Clarke

Vestibular Research Laboratory, HNO-Klinik, Universitätsklinikum Benjamin Franklin, Freie Universität Berlin, 12200 Berlin

As graviceptors, the otolith organs have been of perennial interest in vestibular research, under both terrestrial and microgravity conditions. A number of otolith functions have been identified that indicate the complex interrelations between physiological systems. A review is given of the known otolith functions, including vestibulo-ocular, vestibulo-spinal, vestibulo-autonomic responses, and the current methods for their examination. Particular attention will be given to the role of the otolith function in prolonged microgravity.

N2.6

Neuronal fos activity mapping and video-oculography during cross-coupling stimuli in the gerbil

Galen D. Kaufman

Department of Otolaryngology, University of Texas Medical Branch, Galveston, TX

A four-axis rodent centrifuge (eccentric rate table counterbalanced on a linear bearing to the main vertical axis, with an optokinetic drum and a pitching/rolling platform) was used to apply Coriolis cross-coupling-or Coriolis with centripetal forces to head-fixed gerbils. Binocular two-dimensional eye movements were recorded at 60 Hz using ISCAN equipment. Vestibulo-ocular reflex (VOR) responses in this non-foveate animal include a robust horizontal nystagmus generated by moderate (<0.5 G) rotating centripetal forces. Ocular motor adaptation to cross-coupling developed an asymmetrical hysteresis and large phase changes in vertical eye responses, and a decrease of the horizontal nystagmus over 60 - 90 minutes. Immunohistochemistry for the inducible transcription factor protein Fos-indicative of genomic recruitment and therefore plasticity-revealed differences between animals experiencing identical angular (constant velocity horizontal rotation and simultaneous sinusoidal pitch or roll movements) but not linear forces. Fos protein expression not present in rotation or roll-only control animals occurred in several vestibular-related brainstem areas: the beta and ventrolateral outgrowth subnuclei of the inferior olive (IO), vestibular and prepositus nuclei, vestibulocerebellar granule and Purkinje cells, the supragenual or e-group region, and dorsolateral periaqueductal gray. Strong bilateral hypothalamic and cortical (e.g. insular, piriform, peri- and entorhinal, and cingulate) activity was also present. Some regions produced asymmetric Fos expression depending on the direction of the primary rotation, e.g. the IO subnucleus C and prepositus. One hour for three days of Coriolis training resulted in much less Fos expression throughout the brain, and more stable VOR changes. Thus VOR adaptation behavior can be correlated to simultaneous Fos changes in the brain. Our data provide for the first time a broad neuronal substrate for Coriolis responses. The studies aim to identify and define a neuronal network and explore how it adapts to component motion. (Supported by NIH DC04170)

N2.7

A promising model to investigate the development of firing pattern in the central vestibular system in microgravity

Kenna D. Peusner

Department of anatomy and Cell Biology, George Washington University Medical Center, Washington, DC

In many sensory systems, natural sensory input plays an essential role in the initial formation of connections and membrane properties of CNS neurons. This has not been shown for the otolithic pathways since there is no simple way to deprive the system of gravitational stimulation on Earth. Accordingly, the effects of microgravity on central vestibular development can be studied uniquely in spaceflight. For such studies, a simple model system is advantageous. This is available in the chick tangential vestibular nucleus whose principal cells are second-order neurons participating in the three-neuron vestibuloocular and vestibulocollic reflexes coordinating head and eye movements. For normal reflex function, most mature vestibular nuclei neurons fire repetitively on depolarization. This is an important feature for normal reflex function that is acquired only gradually during chick development. It was found that at 13 embryonic days (E13), all principal cells accommodate after firing a single spike, whereas at E16 only a few cells can fire repetitively (Peusner and Giaume, 1997). Finally, after hatching (H) the vast majority of principal cells fire repetitively. As a first step in understanding the emergence of firing pattern, we analyzed the outward potassium currents and their role in accommodation using patch-clamp recordings on brain slices of principal cells at E16 and H0-3 (Gamkrelidze et al, 1998, 2000). At E16, a low threshold, dendrotoxin (DTX)-sensitive sustained potassium current (I_{DS}) is associated with accommodating principal cells and weakly expressed in firing cells. Blocking I_{DS} transforms accommodating cells into neurons capable of firing trains of action potentials. At H0-3, the mean proportion of I_{DS} contributing to the outward current is significantly less than that reported at E16. These findings indicate that suppression of I_{DS} during development is sufficient to transform accommodating cells into firing neurons and suggests that developmental regulation of this current is required for the establishment of normal vestibular function. Immunocytochemical fluorescence staining with antibodies to Kv1.1 and Kv1.2, known for their sensitivity to DTX, was visualized with confocal microscopy using sections from E16, H1 and H9 chicks (Popratiloff et al., 2001). Staining with both Kv antibodies decreased from E16 to H9. At all ages, principal cells of the same age exhibited differential staining with Kv1.1, while the cells appeared uniformly stained with Kv1.2 but at lower levels than seen for Kv1.1. After hatching, Kv1.1 appeared as clusters restricted to the initial segment, basal dendrites and soma of the principal cells, whereas Kv1.2 decreased significantly in the soma and appeared in the neuropil. In hatchlings, neuron staining with MAP-2, biocytin labeling of primary vestibular fibers and synaptotagmin staining of terminals indicated that Kv1.2 was associated with spoon endings and terminals on the principal cell somas, whereas Kv1.1 was located at postsynaptic sites near spoon endings and somatic terminals. These immunocytochemical results support the electrophysiological findings that I_{DS} is down-regulated around hatching. Presently, little information is available on the earliest development of excitability in vestibular nuclei neurons, including events involved in generating action potentials and the effects of microgravity on these events.

N2.8

Would you want your baby's ears to develop in space?

M. L. Wiederhold, J.L. Harrison

Dept. Otolaryngology, Univ. Texas Health Science Center at San Antonio

What evidence is available suggests that the otoliths of adult animals do not change during space flight. However, several species we have flown on shuttle missions during the period when the otoliths, or their analogs, are first developing, have significantly larger otolith masses than do ground controls. Conversely, developing animals reared on a centrifuge have smaller than normal otoliths. In an attempt to identify a critical period during development for gravitational effects on otolith growth, we have concentrated of several species of fish. In late-stage larvae of swordtail fish (*Xiphophorus helleri*), the growth of the otolith with increasing spine length was significantly greater in the flight-reared animals. However, juvenile fish, 1 cm long at launch, showed no significant difference in otolith size between flight- and ground-reared animals. In very early stage larvae, otoliths were actually slightly larger in the ground-reared larvae. Thus, it appears that late-stage fish embryos reared in space do produce larger-than-normal otoliths, apparently in an attempt to compensate for the reduced weight of the test mass in space. However, the results from very early-stage larvae and juvenile fish suggest that there is a fairly short critical period during which altered gravity can affect the size of the test mass. Fertilized zebrafish (*Danio raria*) eggs were reared on a home-built centrifuge from 6-12 h post fertilization until 1 week of age to determine the effect of rearing in hypergravity. Their results were compared to those of 1-G controls maintained adjacent to the centrifuge. In a few experiments, centrifugation was applied for specific periods during the first week after fertilization. The fine structure of the inner ear at different points of development was studied by both light- and transmission electron microscopy. By 16 hours after zebrafish fertilization (1-G, at 28.5 ^{o}C), precursors of the otoliths are seen in the forming otic vesicle but no sign of a sensory epithelium is present. The first putative hair cells are seen at 24 h after fertilization but only a few stereocilia are seen. An identifiable sensory epithelium, with distinguishable hair cells and supporting cells can be seen by 48 h. By 72 h, adult-appearing hair cells, with a compact bundle of stereocilia, are first seen. At this stage, afferent and efferent synapses are also seen at the base of the hair cells. Thus, from morphological criteria, the hair cells do not appear capable of mechanotransduction until between 48 and 72 hours after fertilization, whereas the otoliths are forming as early as 16 hours post fertilization. Zebrafish reared at 3-G from 1 to 7 days after fertilization exhibited a significantly lower rate of growth of the otoliths with overall fish length than did animals reared at 1-G. Fish exposed to 3-G only from 12-36 h after fertilization had otoliths that tended to be smaller than their 1-G controls, but this difference was not significant. Animals exposed to 3-G from 36h to 7d after fertilization did have significantly smaller otoliths. If the fish use their hair cells to assess otolith weight in a regulatory role, one would not expect this to be possible before the hair cells become functional. Thus the zebrafish reared from 12 to 36 h after fertilization were not significantly affected by the centrifugation probably did not have adequate means of sensing otolith weight to "correct" for the excess weight. Comparable studies have not been performed on developing mammals, which would indicate whether abnormal otolith growth might be expected in higher animals or humans reared in space, as on a deep-space probe or very long-term missions in reduced on micro-gravity. (Supported by NASA NAG2-952 and NAG10-0180)

N3.1

Principles of human gravity orientation and their consequences for weightlessness

H. Mittelstaedt

Max-Planck-Institut für Verhaltensphysiologie, Seewiesen, Germany

To understand human orientation when forces elicited by gravity are absent we need to know how these forces act normally, which phenomena they elicit, which performances they control, which counteractions they provoke. The present contribution will differentiate these effects in a series of sometimes antithetical, sometimes complementary confrontations: 1) Control of posture versus perception of posture; proprioceptive information is indispensable for control, where as it influences perception, if at all, in an indirect or modulatory way. 2) Visual vertical (SVV) versus postural vertical (SPV); both depend on vestibular information; the SVV, however, is also controlled by the idiotropic vector yet not by visceral graviceptors, whereas the SPV is also controlled by visceral yet not by idiotropic input. 3) Open loop versus closed loop control of the SVV; objective accuracy of the SVV depends on open loop calibration, whereas subjective accuracy depends on an internally closed loop. 4) Causally effective versus causally ineffective parameters of the SVV; subjects see and control the angle between the luminous line and themselves, yet not that between luminous line and physical vertical, and hence the former partakes in the formation of the SVV, yet the A- and E-effects do not. 5) The contralateral utricle versus the contralateral semicircular canals as the cause of the ipsilateral bias of the SVV after unilateral neurectomy; the former is contradicted by a recently found equal division of the utricle by the striola, and the persistence of the bias in the horizontal posture, a feature predicted by a model of the latter. 6) Is the idiotropic vector aligned with the head or the trunk? In fact with both, because trunk-fixed and head-fixed vector components are properly oriented by way of neck receptors. 7) How does the visual scene affect the SVV? The verticalizing effect of monopolar visual patterns varies greatly across subjects, in contrast to the stable second or fourth harmonic effect of bipolar or rectangular patterns. 8) Additive versus vectorial effect of rotating visual flow; the former cannot explain the growing asymmetry at growing tilt found by Dichgans and colleagues (1974), whereas a dynamic extension of the idiotropic model does so quantitatively. Consequences of the secured facts and conclusions for the orientation in weightlessness are: 1) Because, due to normalization, the saccular bias becomes plus or minus unity at zero G, its sum with the idiotropic vector should determine the direction and the stability of the SVV. 2) Evidence on a negative correlation between the relative weight of proprioceptive inflow and the size of the idiotropic gain may open opportunities for increasing the latter, hence to promote an egocentrically upright SVV, and thus the orientational stability of an astronaut. 3) Because the z-axis bias of the visceral graviceptors will determine the remaining perception of posture its stability should be well secured in preflight tests. 4) A reliable theory of the otolith-canal interaction is essential for a prediction of the dynamics of orientation in weightlessness.

N3.3

Influence of rotational cues on tilt and translation responses

Daniel M. Merfeld

Jenks Vestibular Physiology Laboratory, Boston, MA

All graviceptors, including the otolith organs, measure gravito-inertial force, which is the vector sum of inertial force due to linear acceleration and gravitational force. Therefore, all graviceptor measurements are ambiguous in that changes in the graviceptor cue can indicate tilt with respect to gravity or translation due to linear acceleration. This ambiguity can only be resolved by utilizing other sensory information. For example, it has been shown here on Earth that rotational cues, provided via vision and the semicircular canals, influence the neural processing of tilt and translation. The evidence for these sensory interactions can be found both in perceptual responses and eye movement recordings. This evidence, demonstrating the importance of rotational cues on the neural processing of tilt and translation here on Earth, will be reviewed and discussed. It not known for certain whether the influence of these rotational cues changes during spaceflight. However, it is reasonable to hypothesize that changes in these neural processes probably occur since rotational cues are no longer needed to help keep track of gravity during spaceflight. Therefore, this talk will also review what is known about how such responses adapt during spaceflight. Such adaptation processes may cause problems when astronauts return to Earth (or land on another planet),since the influence of rotational cues is crucial to accurately calculate the relative orientation during tasks that elicit high-frequency movements of the head, like locomotion. Since these neural processes of sensory integration are crucial to numerous common tasks performed by human subjects like postural control, locomotion and turning corners, this talk will also discuss what research should be done to fill knowledge gaps and what resources will be required to perform this research.

N3.4

Analysis of Spatial Disorientation Mishaps in the US Navy

B.J. McGrath[1], F.E. Guedry[2], A.H. Rupert[3]

[1]Henry M. Jackson Foundation; Rockville, MD; [2]Univ. of West Florida; Pensacola, FL; [3]Naval Aerospace Medical Research Laboratory, Pensacola, FL

Spatial disorientation (SD) and the subsequent loss of situation awareness (LSA) mishaps for military air forces, commercial aviation, and general aviation have an estimated annual cost in the billions of dollars. SD occurs when the pilot has an incorrect perception of the attitude, altitude, or motion of one's own aircraft relative to the earth or other significant objects. One example of the devastating effects of SD is the following mishap. In January 1996, shortly after take off, a US Navy F-14 Tomcat crashed into a residential destroying several homes killing the two aircrew and three people on the ground. Causal factors in the mishap included spatial disorientation and cockpit distraction. To support US Navy mishap boards in their investigations; to provide insight into the problem of SD in naval aviation; and to train aviators to avoid SD mishaps, the Naval Aerospace Medical Research Laboratory (NAMRL) has developed an SD mishap analysis tool that uses spatial orientation models and computer animation techniques to produce three-dimensional computer simulations of SD mishaps Using mishap data from flight data recorders, eyewitness accounts, radar transcripts, and videotapes, an estimation of the pilots' spatial orientation perception is calculated using spatial orientation models. The NAMRL developed model is based on the literature and data from centrifuge, aircraft experiments and aircraft mishaps gathered at NAMRL over the previous 40 years. Results from the NAMRL spatial orientation model - estimated perceived pilot orientation - along with computer models of the actual aircraft and flight data, actual pilot position, is used to develop a three-dimensional computer simulation of SD mishaps. These simulations provide an intuitive tool that permits visualization of a complex problem. In the previous 4 years, results from these analyses have been used in mishap board reports, JAG investigations, congressional hearings, and commercial television. Computer simulations of a F-18 catapult launch mishap, a commercial airline landing mishap, and a recent helicopter mishap will be demonstrated.

N3.5

Perceptual disturbances predicted in zero-*g* through three-dimensional modeling

Jan E. Holly
Department of Mathematics, Colby College, Waterville, Maine

Perceptual disturbances in zero-*g* differ from those in 1-*g*. For example, the vestibular coriolis (or "cross-coupled") effect is much weaker in zero-*g* than in 1-*g*: In 1-*g*, upright subjects rotating in the dark experience perceptual disturbances, including misperceptions of motion and motion sickness, upon head tilt in pitch or roll. However, the effects diminish in zero-*g*, a result that can be puzzling because the zero-*g* and 1-*g* motions have the same cross-coupled angular acceleration—the cross product of the rotation and head-tilt angular velocities. How can perceptual disturbances, or lack thereof, be predicted in zero-*g* for proposed new motion apparatus or environments? The predictions must take into account experimental results in 1-*g* as well as differences between zero-*g* and 1-*g*, and ideally place this knowledge into a common framework to explain differences between zero-*g* and 1-*g*. Presented here is a three-dimensional model designed for complex self-motion perception. The model is used here to investigate vestibular coriolis effects in a centrifuge, both in 1-*g* and in making predictions for zero-*g*. The model and its three-dimensional display have been used previously to explain, for example, why (1) perceived tilt changes immediately and quickly during centrifuge deceleration but not during acceleration, (2) forward tumble is perceived during centrifuge deceleration in a centrifuge whose carriage tilts with the roll tilt of the gravito-inertial force vector, and (3) the vestibular coriolis effect is much weaker in zero-*g* than in 1-*g*. The vestibular coriolis effect's substantial reduction in zero-*g* is explained by the consequences of linear-angular interaction, as displayed in the three-dimensional format of the model. Despite the apparent complexity of this explanation, the model is based upon the scientific principle of Occam's Razor, that the simplest explanation is the most preferable. For motion perception, the laws of physics form the simplest explanation of any phenomenon; e.g. when a subject initially feels stationary, a clockwise acceleration causes a perception of clockwise rotation, just as the laws of physics prescribe. The model's foundation comprises the laws of physics in three dimensions, including all linear-angular and angular-angular interactions, and the vestibular coriolis effect's reduction in zero-*g* is predicted by the model. Investigated here are vestibular coriolis effects during centrifugation. In zero-*g*, will the vestibular coriolis effect be as weak during centrifugation as during on-axis rotation? To address this question, centrifugation in 1-*g* was simulated first, with the subject supine, head toward center. The most noticeable result concerned direction of head yaw: For clockwise centrifuge rotation, greater perceptual effects are predicted for yaw counterclockwise (as viewed from the top of the head) than for yaw clockwise. Once again, analysis of angular vectors will not predict this difference; three-dimensional computations are required. Centrifugation in zero-*g* was then simulated with the same "supine" orientation. The result: In zero-*g*, the vestibular coriolis effect is predicted to be greater during centrifugation than during on-axis rotation. In addition, clockwise-counterclockwise differences do *not* appear in zero-*g*, in contrast to the differences that appear in 1-*g*.

N3.6

Qualitative model of otolith-ocular asymmetry in experiments with vertical eccentric rotation

Alexander V. Kondrachuk
Institute of Physics, Natl. Acad. Sci. of Ukraine

The goal of this work was to outline possible sources of otolith asymmetry, to formulate a simple mathematical model which would allow for the effects of otolith asymmetry to be traced back to experimentally observed ocular reactions in the case of vertical eccentric rotation, to compare the results of modeling with experimental data and to propose new experiments in order to test and correct the model as well as to indicate further possible steps in modeling. The proposed model is based on literary data concerning measurements of ocular-counter-rotation (OCR) and luminous line rotation (LLR) in experiments with vertical eccentric rotation carried out by Wetzig et al. (1990). The model utilizes a number of simplifications and suppositions, the basic of which is linearity of all transformational stages of mechanical input, except for afferents transfer function: the neural response is proportional to otolith acceleration; the otolith-ocular-response is proportional to neural response. The resulting equations link together the centrifugal force effecting otoliths and the angle of the LLR, suggesting that both otoliths control counter-rotation of eyes. Results of the present research show that: 1) despite a number of simplifications the model enables us to reflect the qualitative behavior of the OCR in response to centrifugal acceleration of utricular otoliths including "prevalence-effect", domination of one of "otolith-eye" pairs, absence of one otolith; 2) comparison of theoretical and experimental OCR dependence on acceleration may help estimate the elements of otolith-ocular interaction that are responsible for revealing the effects of otolith asymmetry; 3) results of the modeling indicate further modification of vertical eccentric rotation experiments, which would allow to test and improve the model, as well as to obtain new information on the effects of otolith asymmetry. The model proposed qualitatively imitates the behavior of the LLR in response to centrifugal acceleration of the utricular otoliths and permits analysis of the role of various parameters of the otolith-ocular interaction. Comparison of calculated and experimental dependence of the OCR and the LLR on acceleration can help understand the nature of otolithic asymmetry.

N4.1

Neurophysiological studies of vestibular responses observed during space flight and upon return to earth

Manning J. Correia

Departments of Otolaryngology and Physiology & Biophysics and Anatomy & Neurosciences, University of Texas Medical Branch, Galveston, TX

The initial volume of "The Role of the Vestibular Organs in Space Exploration" presented only one study of direct measurements of vestibular neural activity from the brain stem of a deeply anesthetized cat (Crampton, 1965). Several papers, however, presented corneo-retinal potential representations of the vestibulo-ocular pathways. One involving this author (Hixson et al. 1965), demonstrated that changing linear acceleration could induce a systematic horizontal nystagmus. This was a novel finding but it was unclear at that time whether the otolith organs or the semicircular canals produced the nystagmus. Within the next decade it became known that appropriate stimulation of either the semicircular canals or the otolith organs could produce a systematic, stimulus-locked nystagmic response. Two papers (Lansberg, 1965; Milovic, 1965) showed that nystagmus induced by head rotation or caloric stimulation could be modified by concomitant static linear acceleration. These results are now dogma. The 1970s were very productive years for ground-based studies of vestibular neurophysiology. In subsequent decades, neurophysiological studies were extended to space flight. Yet careful and thorough electrophysiological studies during space flight to dissect out the contribution of *any* of the synaptic relay stations underlying the vestibulo-ocular or vestibulo-spinal responses remain to be done. This is critically needed knowledge since it must be determined how information from the vestibular end organs is modified as it courses to the brain, eyes and extremities during extended periods of micro-gravity. Anatomical studies suggest that space flight modifies the synaptic structures related to the hair cell-primary afferent synapse. Does this modification alter the primary afferent response to produce non-veridical perception and locomotion? While it is known from ground-based studies that the central vestibular pathways and other neural structures modify the peripheral vestibular neural response, there are no single neuron and only a few published multi-neuron recordings from these pathways and structures during or immediately following space flight. This information is needed since space flight results during the past three decades have taught us that it is not just the peripheral vestibular response but the entire space flight experience acting on the entire body, and it's diverse systems, that determines the individual's vestibular response to head rotation and translation during and following flight.

If questions like those posed above are to be addressed rigorously and successfully in the future, four things are needed: a laboratory in space with sufficient committed payload specialist time, commitment to an investigator for a series of investigations, a primate model and an on-board centrifuge. Electrophysiological experiments are tedious and time consuming. Furthermore, the response of one to 20 neurons does not necessarily characterize the response of 5000 nerve fibers or neurons. If ambiguous results are produced in one experiment, the investigator deserves the chance to replicate his/her experiment once or maybe twice. Compelling rationale can be provided for conducting behaving primate neurophysiological experiments during and after space flight (Correia, 2002). Historically, other than man, the behaving monkey has been studied most during American and Russian space flights. The scientific method and reliable results demand experimental controls. An on board centrifuge, equipped for electrophysiological studies, is not debatable. It is an essential component for scientifically acceptable vestibular electrophysiological space research (Correia, 1998).

N4.3
Vestibular suppression during space flight

Douglas Watt
Aerospace Medical Research Unit, McGill University, Montreal, Canada

Transient cancellation (suppression) of the vestibulo-ocular and vestibulocolic reflexes is a normal part of every large amplitude gaze refixation. Usually, eye and head rotations occur rapidly and the "duty cycle" of suppression is very small. However, if it becomes excessive, the way in which labyrinthine signals are processed is gradually altered. Until normal function is restored, even normal vestibular inputs are considered erroneous and motion sickness can result. Studies have shown that voluntarily fixing the head to the torso as if wearing a neck brace prolongs head movements. This increases the "duty cycle" of suppression and can be enough to provoke symptoms in susceptible subjects. A similar motor strategy is often adopted during the weightlessness of orbital or parabolic flight. While this can be a means of reducing head movements to combat motion sickness, it often precedes the onset of symptoms. Could inadvertent and excessive vestibular suppression be contributing to the development of space motion sickness. In a recent experiment, we monitored the eye, head and upper torso rotations of four crew members. All showed a significant increase in gaze slip during spontaneous, self-generated head movements on flight day one. This implied a less effective use of visual and vestibular inputs and could not be considered normal behavior. Head angular velocities measured at that time were mostly below 100 degrees/sec, suggesting an active suppression of visual and vestibular mechanisms rather than a simple decrease in vestibulo-ocular reflex gain resulting from altered otolith stimulation. If the latter had been true, visual tracking should have been effective in maintaining gaze on target. Thus, there was some evidence that increased vestibular suppression was occurring during space flight. Furthermore, this amount of increased suppression would have been more than adequate to produce motion sickness in susceptible individuals on the ground. It is not so clear if it would have been enough to cause other signs or symptoms. This would have depended on the degree to which vestibular sensitivity had been changed by the excess suppression, which can vary between individuals. In addition, suppression-induced changes in vestibular sensitivity recover spontaneously and this would have been occurring whenever the head was stationary. The likelihood of other signs or symptoms being present would probably have depended on the individual and on his or her recent movement history, leading to extremely variable effects. Motion and gravito-inertial environments that go beyond the normal operating range of the vestibular system (e.g. riding in a car or spacecraft) can lead to motion sickness. Inadvertent and excessive vestibular suppression (reading a book in that car or doing something equivalent in the spacecraft) will make it worse. Future research should define what "something equivalent" means, possibly leading to behavioral changes that could reduce symptoms. In addition, since it is possible to adapt to motion sickness caused by excessive vestibular suppression, and the protection obtained appears to transfer to other environments, the possibility of pre-adapting crew members using this quite different approach should be studied. (Supported by the Canadian Space Agency and the National Aeronautics and Space Administration)

N4.5

The readaptation of utricular nerve afferents to earth's 1g following exposure to microgravity

R. Boyle[1], S.M. Highstein[2], A.F. Mensinger[3]

[1]BioVIS Technology Center, NASA, Ames Res. Center, Moffett Field, CA; [2]Dept. Otolaryngology, Washington Univ., St. Louis, MO; [3]Dept. Biology, Univ. Minnesota, Duluth, MN

Vertebrates possess the utricular organ of the inner ear, comprised of a mechanosensitive hair cell neuroepithelium, gel layer and a weight-lending otolith mass. External accelerations due to head translation and head tilt relative to gravitational vertical displace the hair cell bundles relative to the otolith mass, initiate the transduction process that transform the vector sum of the imposing accelerations into a neural code carried by the afferent nerve fibers. This code is combined in the central vestibular pathways with motion signals obtained from the semicircular canals and other sensory modalities to compute a central representation of the body in space called the gravitoinertial vector. Thus an abnormal otolith component should have profound effects upon the orientation of the organism, and has been hypothesized to be causal in vestibular disorientation or space adaptation (to microgravity) and readaptation (return to Earth's 1g) syndromes. We studied the neural readaptation to Earth's 1g using electrophysiological techniques to measure the response characteristics of utricular nerve afferents in toadfish, *Opsanus tau*, upon return from a 9-day (STS-95) and 15-day (STS-90) exposure to microgravity aboard two NASA shuttle orbital flights. Postflight single afferent responses to gravito-inertial accelerations were collected and compared to afferent responses of control animals similarly tested. Six recording sessions were made sequentially 10-117 hrs postflight. Afferent responses to translational accelerations and head tilts were detected in the earliest sessions. The most striking result is the occurrence of hypersensitive afferents, having nearly saturating discharge modulation to such minor displacements of < 0.5 mm displacement at 0.006g, within the first day postflight; on average the population of the first day postflight showed a three-fold increase in response sensitivity. After about 30 hrs the afferent response properties of flight and control fish were similar. The microgravity exposure in orbit apparently resulted in a temporary up-regulation of the sensitivity of utricular afferents. The time course of return to normal afferent sensitivity parallels the decrease in vestibular disorientation in astronauts following return from space. (Supported by NASA, NIH and NASDA)

N4.6

Effects of varying linear acceleration on the vestibular-evoked myogenic potential (VEMP)

David Solomon, Vinay Singh, Romesh Khumbani, Adam Jenkins

University of Pennsylvania, Philadelphia, PA

The vestibular-evoked myogenic potential (VEMP) may be recorded from the sternocleidomastoid muscle (SCM) in response to high-intensity clicks or short tone bursts delivered to the ipsilateral ear. Vestibulocollic pathways originating in the sacculus, which is naturally stimulated by linear acceleration, mediate this response. It is not known whether the level of ambient gravity, or the orientation of the head with respect to the direction of gravity, affect this response. Microgravity must have a profound effect on afferent information from the sacculus, however ocular motor responses from the sacculus are poorly characterized. If the VEMP were found to vary in a systematic way depending upon the g forces acting on the sacculus, this could provide a useful window onto saccular function during adaptation to microgravity. Five normal subjects were positioned on a tilt table at 5 different orientations: upright (+90°), upside down, horizontal and +/-45°. This resulted in a projection onto the head z-axis of -1, -.707, 0, .707 and 1 g. Two trials were performed non-consecutively, and the order of each orientation was randomized. Clicks were delivered at 5.1 Hz to one ear at 95 dB. Surface electrodes over the SCM recorded EMG activity which was averaged offline using the click onset as a trigger. Subjects maintained a fixed level of contraction by viewing indicators of EMG rms value while the head was forcefully turned away from the stimulated ear. The latency of the P1 and N1 peaks, as well as the P1-N1 amplitudes were determined at each orientation. The mean rms value of the ongoing EMG activity during stimulation was used to normalize the responses, since P1-N1 amplitude has been found to vary with the level of muscle contraction. Informed consent was obtained from all subjects. Responses were included for analysis only if the following conditions were met: a P1 peak was identified between 8 and 15 ms, an N1 peak between 15 and 33 ms, and the P1-N1 amplitude was greater than twice the maximum value of the signal-averaged response in the 20 ms interval before the click (baseline noise level). Using these criteria, only 2 subjects had at least one reliable waveform at each angle. Head down orientations were more likely to yield excluded data. There was no significant correlation between head orientation and P1 latency, P1-N1 amplitude or mean rms EMG activity. In

EMG activity. In this pilot study, no evidence was found for an effect of saccular loading on the VEMP. It is possible that larger magnitude changes in g level could affect the response, and experiments on a short-arm centrifuge are underway to explore this possibility. Primary afferents from the primate sacculus have different baseline discharge rates depending upon their excitation by either +z or –z acceleration. It would appear that the mechanism by which sound activates saccular afferents is relatively insensitive to the firing rate of tonic neurons. This suggests the possibility that the VEMP is generated predominantly by afferents with more phasic responses. (Supported by NIDCD K23-DC-00165 and Whitaker Foundation RG-97-0496)

N4.7

Effects of gravity deprivation on the development of vestibuloocular reflex and fictive swimming in lower vertebrates (*Xenopus laevis, Oreochromis mossambicus*)

Eberhard Horn, Sybille Böser

Gravitational Physiology, University of Ulm, Ulm, Germany

Sensory deprivation during early periods of life affects the development of many sensory and motor systems and causes long-lasting or even irreversible modifications of their morphology and/or physiology. Exposure to microgravity offers the only possibility to study effects of sensory deprivation on the developing sense of gravity. We have studied this question in an amphibian (*Xenopus laevis*) and a fish (*Oreochromis mossambicus*) using the roll-induced static vestibuloocular reflex (rVOR), and, for *Xenopus* only, the activity of spinal ventral roots, which correlates with swimming activity. Experiments could be performed due to flight opportunities during the German D-2 mission (1993), the Shuttle-to-Mir mission SMM-06 (1997) and the Soyuz taxi flight Andromeda (2001) which offered deprivation durations of 9 to 10 days. At launch, animals were 2-4 or 8-10 days old; the younger ones had not yet developed the rVOR at µg-onset while the older ones had already developed the rVOR. All flight and ground animals were tested for their rVOR; tadpoles from the Andromeda flight in 2001 were also used to measure their ventral root activity during fictive swimming. Stage-matched samples were used to compare µg- with 1g-animals. The main observations were: (1) In the young *Xenopus* tadpoles, microgravity induced a depression of the rVOR, in particular in those animals which developed upward bended tails during their space flight; in the older ones, the rVOR was also depressed if the tadpoles developed upward bended tails while the rVOR was augmented in the tadpoles with a normal body shape. (2) In young fish *Oreochromis*, the rVOR was augmented after termination of microgravity while the older group revealed no difference with respect to the ground control. In contrast to *Xenopus*, young fish never developed upward bended tails during µg-exposure. (3) Recordings from the ventral roots of the spinal cord in *Xenopus* tadpoles revealed significant effects of a 10-day microgravity exposure on fictive swimming: the duration of episodes of fictive swimming increased and the duration of the rostrocaudal delay decreased compared to 1g-reared tadpoles; in addition, a slight decrease of the burst duration of fictive swimming was recorded. The main hypotheses are: (1) The effect of gravity deprivation depends on the age of the animals at onset of microgravity. (2) The rVOR development is retarded in very young stages and accelerated in older ones the latter postulation due to an adaptive sensitization of the developing vestibular system during µg-exposure, while very old stages become insensitive to gravity deprivation or perform a very fast 1g-readaptation after temination of microgravity. (3) Considering our data correlations, we postulate that a microgravity-induced reduction of macula activity affects the development of descending projections to the spinal cord. (Supported by grants from the German Space Agency (DLR))

N4.8

The neurobiology for a sense of direction: an update from on the ground, upside down, and space-bound

Jeffrey S. Taube[1], Jeffrey L. Calton[2], Robert W. Stackman[3], Charles M. Oman[4], Megan S. Steven[1]

[1]Dartmouth College, Department of Psychological & Brain Sciences, NH; [2] California State University, Sacramento, Department of Psychology, CA; [3] Oregon Health Sciences University, Department of Behavioral Neuroscience, OR; [4] Massachusetts Institute of Technology, Man Vehicle Laboratory, MA

Previous studies have identified neurons in the rat brain that encode the animal's directional heading in absolute space and may be involved in navigation. These head direction (HD) cells discharge selectively when the rat points its head in a specific direction (the preferred firing direction) in the horizontal plane, independent of its ongoing behavior. Vestibular information is believed critical for the generation of the HD signal because labyrinthectomies abolish direction-specific firing in these cells. The preferred firing direction of HD cells can be controlled by both landmark cues and idiothetic cues, such as vestibular, proprioceptive, and motor efference copy. Previous experiments have shown that HD cells continue to discharge when the rat is locomoting in the vertical plane, provided the vertical locomotion begins with the rat's orientation corresponding to the cells' preferred firing direction. One model that is consistent with these data is that HD cells define the horizontal reference frame as the animal's plane of locomotion. This model would hypothesize that directional cell firing should be maintained when the animal is locomoting upside-down on the ceiling. The present studies examined HD cell responses when a rat was 1) locomoting on the ceiling in 1-g, 2) locomoting on the floor, wall, or ceiling of a rectangular box in 0-g, and 3) made disoriented by spinning on a turntable in 1-g. When locomoting on the ceiling in 1-g, the majority of HD cells ceased discharging in a direction-specific manner, and background firing rates increased compared to rates on the floor and wall. For the few cells that maintained directional firing on the ceiling the preferred firing direction was usually aligned to the recording room reference frame. When HD cells were monitored in 0-g (NASA parabolic flights), HD cells responded normally when the animal was on the floor of the box, but lost their direction-specific firing when locomoting on the walls and ceiling of the box. Again, when cells lost their direction-specific firing, there was a general increase in overall background firing. There were a few occasions on the ceiling when cells discharged with a burst of spikes in a direction 180° opposite from where it discharged when the rat was on the floor, suggesting the animal may have experienced a visual reorientation illusion during those moments. For HD cells in animals that were spun on a turntable rapidly in the dark in 1-g (~270°/sec), HD cells lost their direction-specific firing and had a concomitant increase in background firing rate. The firing patterns observed from HD cells when animals were presumably disoriented by being spun on the turntable were similar to the patterns observed from HD cells when the animals were locomoting on the ceiling in 1-g, and on the walls and ceiling in 0-g. These results suggest that HD cells lost their direction-specific firing on the ceiling in both 0-g and 1-g, and on the wall in 0-g, because the animals were explicitly disoriented. Alternatively, perceptual disorientation may arise because of the loss of directional activity in HD cells.

N5.1

Main results of Russian experimental program on the "MIR" station

Inessa B. Kozlovskaya, Anatoly I. Grigoriev

RF SRC Institute for Biomedical Problems, Moscow, Russia

28 space crews have accomplished successfully their missions on "MIR" station lasting from 125 days to 1 year or longer (e.g. 438 days). 93 cosmonauts and astronauts including 24 international crewmembers from 10 countries provided jointly more than 1700 biomedical experiments, 1255 of which were dedicated to medicine and physiology, 93 -to biology. The main goals of these studies were perfecting medical support and medical care systems for long duration space flights, obtaining new data on mechanisms of adaptations of different body systems to weightlessness and testing new perspective technologies, methods and means of life/medical support in long term space flights. The specific features of biomedical studies on "MIR" station were determined by wide international cooperation and advanced integration of national and international programs (Bulgarian, Austrian, French, American), by increased time granted to biomedical studies in the number of missions (main crews 3, 15 – 19) and by high technological support of the majorities of the experiments. As a result a large amount of new data concerning the sensory-motor adaptations, muscle and bone plasticity, cardiovascular control, metabolic and hormonal activities, increasing our knowledge of human biomedical responses to space environment have been obtained, that allowed to justify some of previously made hypothesis and to bring together some of previously diverse points of view. This condition happened to be true for the conclusions on i) the increased vestibulo-oculomotor and vestibulo-motor gain at the first stage of adaptation to microgravity and on the suppression of the motor reactions to the vestibular stimuli during the later phases; ii) on the reorientation of motor control systems during long stay in weightlessness predominantly to the visual stimuli; iii) on multifactor nature of disturbances of posture, eye-head coordination at different stages of exposure to weightlessness; iv) on important role of the support (weight-bearing) afferentation in the posture control system; v) on two factor nature (peripheral and central) of postural muscle fibers' deterioration under conditions of microgravity; vi) on possibilities to compensate most of negative effects of weightlessness by adequate muscle loading. The results of studies laid a base for further perfection of the countermeasures system in the long term space flight.

N5.2

Assessment of neurologic function following short duration spaceflight utilizing a standardized rating scale

J. B. Clark

Space Medicine & Health Care Systems Office, NASA Johnson Space Center, Houston, TX

The most common neurologic difficulties encountered in spaceflight are space motion sickness (SMS) and post-flight neurovestibular symptoms. Understanding neurologic adaptation to microgravity will allow for mission objectives to be met and enhance productivity. High risk tasks requiring optimal neurologic function on orbit include rendevous and docking, robotic operations and extravehicular activity (EVA). Neurologic readaptation to gravity is crucial for piloted entry and landing. Post flight activities such as egress from the spacecraft, also require a high degree of performance. In order to assess various factors related to SMS in-flight and neurovestibular dysfunction post-flight, an extensive database was created incorporating astronaut medical debrief forms, astronaut aeromedical summary information, and the Neurological Function Rating Scale form from short duration U.S. Space Shuttle missions. The Neurological Function Rating Scale form was developed as a standardized means of assessing neurological status associated with spaceflight. This scale was implemented in November 1996 with mission STS-80. It is administered as part of the astronaut physicals conducted pre-flight, on landing day, and post-flight. The assessment is conducted by the NASA flight surgeon, as are the astronaut medical debriefs, which also use a structured format. The Neurological Function Rating Scale assessment is usually conducted by the NASA flight surgeon one to four hours after landing, after the crew have egressed the spacecraft. The Neurological Function Rating Scale form consists of a series of eleven categories of neurological symptoms and signs/ performance measurements scored between 1 (no symptoms or normal performance) and 4 (persistent symptoms or severe performance decrement) as determined by the NASA flight surgeon. A total score between 11 (all 1s) and 13 is regarded as normal, 14-15 as suspect, and a score greater than 15 is considered for referral to the neurovestibular lab for posturography, gaze, and locomotion testing (see Neurological Function Rating Scale form). Subsets of the Rating Scale may relate to operational performance effects. The first subset evaluates subjective neurological symptoms (headache, dizziness/faintness, and vertigo/spinning), which could distract crewmembers from tasks and duties. The next subset deals with motor performance skill, which could influence vehicle control, particularly reentry and landing phases. Proper functioning of gaze and ocular movements is critical to the acquisition and interpretation of visual displays. Neurological disturbances associated with spaceflight may result in delay or incorrect interpretation in the acquisition and processing of visually acquired information. The third subset of Neurological Function Rating assesses gait and station, which are vital to emergency egress. Data within the database created and analyzed in this study is solely from U.S. Space Shuttle missions launched between the dates of November 19, 1996 and February 11, 2000 (STS-80 through STS-99). The database accounts for 112 astronauts, 88 of which are male and 24 of which are female. A payload specialist who was outside the general astronaut age was excluded from the analysis. Statistical analysis of database parameters included age; sex; height; crew position; mission activities; mission duration; prophylactic, in-flight, and post-flight medication use for space motion sickness or neurovestibular symptoms; episodes of vomiting in-flight; post flight orthostatic intolerance (PFOI), postflight treatment for neurologic symptoms or orthostasis, previous spaceflight experience; time lapsed since last spaceflight; severity of space motion sickness and neurovestibular disturbances in previous flight; and flight surgeon rating of likelihood of successful egress from the side or overhead hatches. The most severe neurological spaceflight deficits on the Neurological Function Rating Scale are the Gait and Station subset. Commanders and pilots may have a more stable landing day performance than other crewmember positions for total score on the Neurological Function Rating Scale tests. Gaze and ocular movement function is affected after spaceflight. The neurovestibular rating score from previous flight is a good predictor for the probability of distribution of failure index scores in this database. Previous flight experience may result in less performance deficit on post-flight Neurological Function Rating Scale test scores, particularly within the Gait and Station subset. Space motion sickness and neurovestibular symptom scores from previous flights are likely to be good predictors for space motion sickness, though both may be contributing through separate mechanisms.

N5.4
Space motion sickness symptomatology: 20 years' experience of NASA's space shutttle program

James Locke
NASA, Johnson Space Center, Houston, TX

Although motion sickness is a common malady among humans traveling to space, the nature of "space motion sickness" is not widely-known. Like terrestrial motion sickness, the intensity and quality of symptoms can vary widely from individual to individual. However, the more than 100 Space Shuttle Missions successfully completed during the first twenty years of the Space Shuttle Program allowed hundreds of individuals to experience the microgravity environment of Space. By compiling post-mission medical debrief reports, individual medication logs and post-mission interviews has yielded insight into the symptomatology of motion sickness experienced during short duration spaceflight. In turn, this knowledge can be used to minimize the operational impact of space motion sickness through astronaut training, mission scheduling, and the use of appropriate medication.

N5.5
Neurovestibular effects of long-duration spaceflight: a summary of Mir phase 1 experiences

Jason T. Richards[1], Jonathan B. Clark[2], Charles M. Oman[1], Thomas H. Marshburn[2]
[1]Man Vehicle Laboratory, Massachusetts Institute of Technology, Cambridge, MA; [2]Space Medicine and Health Care Systems Office, NASA Johnson Space Center, Houston, TX

Space motion sickness and associated neurovestibular dysfunction have been relatively well characterized on short-duration (1-2 week) Space Shuttle missions. Between March 1995 and June 1998, seven NASA astronauts flew on the Russian Mir space station, some for up to six months in duration, as "Phase 1" of the effort to build the International Space Station. The purpose of this paper is to provide a summary of the available information on the neurovestibular dysfunction experienced on these flights, based on an incomplete set of medical questionnaire and interview data from the NASA-Mir Phase I program. All references to specific crewmembers were removed to respect their individual privacy. Data were compiled by epoch (in-flight vs. landing/postflight) and grouped by neurovestibular topic. Sense of spatial orientation took longer to develop, spatial illusions were more easily induced, and space motion sickness symptoms were worse inflight. Upon returning to Earth, head movements caused illusory spinning sensations for up to 7 days postflight and balance control did not fully recover for at least a month. It is clear that long-duration Mir crewmembers experienced neurovestibular dysfunction that was usually more intense and longer in duration than on shorter flights. The differences appear associated to mission duration and vehicle size and architectural complexity.

N5.6
Development of improved motion sickness management in the NASA reduced gravity parabolic flight KC-135 ("Vomit Comet") program

James Locke
NASA, Johnson Space Center, Houston, TX

The NASA Reduced Gravity Program utilizes a KC-135 aircraft (the "Vomit Comet") flying in parabolic arcs to provide a microgravity environment in which to conduct space-related research. Motion sickness is a significant problem among KC-135 flyers, limiting researchers' productivity and adversely affecting their personal experience with microgravity. To mitigate this problem, a comprehensive overhaul of the Reduced Gravity Programs' motion sickness management was performed. This process included the development of novel performance-based motion sickness questionnaires, defining effective behavioral strategies to combat motion sickness during parabolic flight, and the tailoring of anti-motion sickness medication to this unique environment. The implementation of these improvements has led to a decrease in the incidence of motion sickness from approximately 70% among first-time flyers down to approximately 20%. These improvements can aid in improving the impact of motion sickness in other operational motion environments, such as during spaceflight.

N5.7

Neurovestibular symptoms following space flight

Kira Bacal[1], Roger Billica[2], and Sheryl Bishop[3]
[1]Medical Informatics & Health Care Systems, NASA-Johnson Space Center, Houston, TX; [2]Ft. Collins, CO; [3]UTMB, Galveston, TX

Neurovestibular symptoms experienced by astronauts in the post-flight period were examined using data from medical debriefs contained in the NASA Longitudinal Study of Astronaut Health database. Ten symptoms were identified (difficulty concentrating, persisting sensation aftereffects, nausea, vomiting, vertigo while walking, vertigo while standing, difficulty walking a straight line, blurred vision, dry heaves), of which eight were crossed with twelve demographic parameters (mission duration, astronaut gender, age, one-g piloting experience, previous space flight experience, g-suit inflation, g-suit deflation, in-flight space motion sickness, in-flight exercise, post-flight exercise, mission role, fluid loading). Three symptoms were experienced by a majority of crewmembers, and another two by more than a quarter of the crew. Intensity of the symptoms was mild, suggesting that they are unlikely to pose a risk to the crew during landing and the post-flight period. Seven of the symptoms and eight of the parameters under study were found to be significantly associated with each other. Clumsiness, persisting sensation aftereffects, and difficulty in walking a straight line were encountered in the majority of astronauts following spaceflight, generally to a mild degree. Future studies may choose to focus on determining causality in these relationships.

N6.1

Human spatial orientation and navigation in weightlessness

Charles M. Oman
National Space Biomedical Research Institute and Man Vehicle Laboratory, Massachusetts Institute of Technology, Cambridge MA

When astronauts enter weightlessness, they report no sensation of falling, and normal head movements rarely elicit disorientation and oscillopsia as they often do in vestibular patients on Earth. However most crewmembers experience a compelling "inversion illusion" for a few minutes after main engine cut off. Inversion illusion recurs in some individuals during the first several days in orbit. The majority of crewmembers also report visual reorientation illusions ('the downs") when they leave their seats and float sideways or upside down in the cabin, or see another person doing so. The sudden realignment of cognitive reference frame results in a change in the subjective identity of surrounding surfaces (e.g. ceiling seem like floors). Crewmembers also report occasional problems with spatial memory, and difficulties making 3D spatial judgments between modules, particularly those whose visual verticals are not coaligned. Inversion and visual reorientation illusions can trigger episodes of space motion sickness during the first days in orbit. However, visual reorientation illusions and associated spatial memory and navigation difficulties apparently persists for months. Spacelab experiments have shown that absence of gravireceptor and haptic cues makes crewmembers more susceptible to visually induced angular and linear self-motion sensations (circular- and linear-vection). Some spacewalking astronauts have reported height vertigo and enhanced sensations of orbital velocity. This paper will review theories and related ground and flight research aimed at establishing the physiological and psychophysical basis of these 0-G spatial orientation and navigation problems, and discuss existing and potential countermeasures. (Supported by NASA Cooperative Agreement NCC9-58 with the National Space Biomedical Research Institute.)

N6.2

Spatial perception changes associated with space flight: implications for adaptation to altered inertial environments

D. E. Parker
Department of Otolaryngology-HNS, University of Washington, Seattle, WA

Preparation for extended travel by astronauts within the Solar System, including a possible manned mission to Mars, requires more complete understanding of adaptation to altered inertial environments. Improved understanding is needed to support development and evaluation of interventions to facilitate adaptations during transitions between those environments. Travel to another planet escalates the adaptive challenge because astronauts would experience prolonged exposure to microgravity before encountering a novel gravitational environment. This challenge would have to be met without ground support at the landing site. Evaluation of current adaptive status as well as intervention efficacy can be performed using perceptual, eye movement and postural measures. Due to discrepancies of magnitude and time-course among these measures, complete understanding of adaptation processes as well as intervention evaluation requires examination of all three. Previous basic science and clinical research that provide models for comprehending adaptation to altered inertial environments are briefly examined. Selected pre- in- and post-flight perceptual data from astronauts are summarized. Selection is based on relevance for determining adaptive state and / or evaluation of possible interventions. Finally, based on apparent gaps in our current knowledge, further research needed to achieve the goals of understanding and intervention development is proposed. (Supported by NASA Grant NCC 9-56.)

N6.3

Reference frames involved in navigation inside of 3D-complex environments

Manuel Vidal, Michel-Ange Amorim, Alain Berthoz
Laboratoire de Physiologie de la Perception et de l'Action College de France /CNRS Paris France

Although recent studies have brought new insights concerning the mechanisms of spatial memory and cognitive strategies during navigation, most of these studies have concerned 2D navigation and little is known concerning the problem of 3D spatial memory. We have studied the influence of the relation between egocentric and allocentric frames of references on memorisation of complex 3D-structured environments These environments could represent buildings with several floors or a space station. Navigation in the presence of gravity ascribes one's displacement to a 2D surface where only self-motion including yaw rotations are considered and eventually vertical translations at vertical junctions. In contrast, in weightlessness one can move along or turn about any axis.

In a first experiment, we have compared three displacement conditions on the recognition of the virtual 3D-maze travelled. Each of the visual-displacement stimuli used a different set of rotations at junctions between segments, favouring different reference frames. The *terrestrial condition* maintained subjects' heads upright all along the trajectory, and going up and down was done facing the walls. The *subaquatic condition* maintained subject's head upright in horizontal segments, but in vertical segments gaze was oriented vertically. The *weightless condition* used the unique rotation (among the three rotations of space) orienting the line of sight parallel to the next segment. Subjects indicated which corridor they traversed among 4 different corridors presented from an outside perspective. The results showed that the *terrestrial* condition allowed a better recognition of the mental representation built during exploration, and that the *weightless* condition provided the worst performance, especially for complex 3D-structures. These results suggest that although humans can build a cognitive map of a 3D-structured environment, their neuro-cognitive functions appear to be specialised for 2D navigation and are not appropriate for *weightless* exploration. The more frequently the egocentric and allocentric verticals were aligned, the easier was the construction of the mental representation of the 3D maze.

In a second experiment, we wanted know what in the *terrestrial* condition lead to better performances. There were actually three aligned axes that could facilitate the reference shift required by the task: the gravity's axis, the body's vertical axis and the displacement's rotation axis. We have dissociated this alignment by 90º-tilting either subject's body (lying on their sides), either the projected video of the displacement (rotated or not relatively to subject's position). This gave four sub-conditions that were compared to each other and with the *weightless* condition. The task was a computerised 3D-reproduction of the shape of the maze. The results showed that there are two different groups of subjects, those relying more on the gravity axis and those relying more on the body axis as reference frames for memorisation. These groups are correlated with the field dependency factor determined by the classical rod and frame test. Performances were always lower when one of the three axes was not aligned with the two others. We concluded that reference frames for memorisation of the environment can be either defined by gravity either by the body axis, and when they are not consistent performances decrease.

The third experiment was sent on board of the International Space Station and three cosmonauts were involved in this study. Since gravity could provide the reference frame for the *terrestrial* condition, we wanted to check if the suppression of sensed gravity would change the relative performances of *weightless* and *terrestrial* condition. Results apparently indicate that the suppression of sensed gravity (Berthoz, 1999) doesn't affect at short term the performances of each condition, but could affect performances at long term in longer flights.

N6.4

Spatial orientation of the vestibulo-ocular reflex (VOR) in microgravity: Results from the Neurolab STS-90 and Cosmos 2044 and 2229 missions

Steven T. Moore[1], Gilles Clement[2], Mingjai Dai[1,3], Theodore Raphan[4], Bernard Cohen[1,3]
[1]Dept. of Neurology, Mount Sinai School of Medicine, New York, NY; [2]CNRS, Toulouse, France; [3]Dept. of Physiology and Biophysics, Mount Sinai School of Medicine, New York, NY; [4]Dept. of Computer and Information Science, Brookyln College of CUNY, Brooklyn, NY

Four rhesus monkeys were tested before and after 12 days in orbit on COSMOS flights 2044 (1989) and 2229 (1992-93). Eye movements were measured in 3D using scleral search coils. We tested the horizontal, vertical and roll angular VOR with steps of velocity and the orientation of ocular counter-rolling (OCR) and vergence with off-vertical axis rotation (OVAR), and the orientation of optokinetic after-nystagmus (OKAN) to gravito-inertial acceleration (GIA). The only change in angular VOR gain was a decrease in roll of 30% in two animals. There was a long-lasting (11 day) decrease in both post-flight OCR (70%) and vergence in response to naso-occipital linear acceleration (50%) during static tilts and OVAR. The spatial orientation of OKAN was shifted towards the body vertical (28°).

Four astronauts were exposed to 0.5- and 1-g centripetal accelerations directed along either the interaural axis (Gy centrifugation), or the head dorsoventral axis (Gz centrifugation) during the 1998 16-day Neurolab (STS-90) mission. Eye movements were measured in 3D from video with the subject in darkness and while viewing an optokinetic stimulus (OKS) and smooth pursuit targets moving at 30°/s. OCR was unchanged during pre- and post-flight 1-g Gy centrifugation (5.7° and 5.9°, respectively). There was a small decease in in-flight OCR (5.1°). OCR during static tilt was unaltered pre- and post-flight. OCR during static tilt was always less than OCR elicited by centrifugation on Earth, but equivalent to OCR generated by in-flight centrifugation, for an equivalent interaural linear acceleration. The OKN axis during horizontal OKS tilted 6.4° and 9° towards the GIA during 0.5- and 1-g Gy centrifugation, respectively. During 1-g Gz centrifugation the OKN velocity axis tilted 5.5° in the pitch plane towards the GIA during horizontal OKS. The orientation of OKN to the GIA was not altered during in-flight centrifugation or after landing. During horizontal OKS and static roll tilt the OKN axis tilted 6.3° and 9.5° towards the GIA at 30° and 90° of tilt, i.e., at interaural linear accelerations of 0.5- and 1-g, respectively. Smooth pursuit was aligned with the visual stimulus in all conditions and tilts of the GIA did not alter the direction of visual following.

The COSMOS results indicate that there can be considerable short- and long-term changes in otolith-induced orienting eye movements after adaptation to microgravity in monkeys. In contrast, OCR and spatial orientation of OKN were unaffected in the four Neurolab astronauts. OKN eye velocity oriented to the GIA through velocity storage through both pitch and roll. OKN tilts and in-flight OCR were of the same magnitude for an equivalent interaural linear acceleration during centrifugation or static tilt, which suggests that these responses were primarily generated by interaural stimulation of the otoliths. Ocular pursuit had no orientation properties. One possible explanation for the disparity between the COSMOS and Neurolab results, currently under investigation, is that exposure to 'artificial gravity' during the Neurolab flight acted as a countermeasure to deconditioning of otolith-ocular reflexes. (Supported by NASA grants NAS 9-19441, NAG 2-573, NAG 2-703 and NCC 9-128).

N6.5
Effects of parabolic flight zero-gravity on looming linear vection

Andrew Liu, Kevin Duda, Charles M. Oman, Alan Natapoff
Man Vehicle Laboratory, Massachusetts Institute of Technology, Cambridge, MA

We investigated the sensation of illusory linear self-motion ("vection") in the 0-g phases of parabolic flight during a CNES-sponsored campaign. We compare our results to a related 1998 space shuttle investigation (STS-90) that found latency to the onset of vection decreased and the average magnitude of vection increased while free-floating in weightlessness. The data were collected on three subjects with previous parabolic flight experience on consecutive flight days (30 parabolas/flight) before, during, and after the flights. During the tests, subjects sat facing forward on the floor of the plane and wore a head mounted display (HMD) (Kaiser ProView-80). They viewed stereoscopic images of a long virtual corridor were displayed at 60Hz, simulating linear motion down its long axis for ten seconds at one of four different speeds (0.4, 0.6, 0.8, or 1.6 m/s). Subjects deflected a gamepad joystick to indicate the percentage of the visual motion that they attributed to self-motion (%saturation). Zero deflection indicated no sense of self-motion; full deflection indicated that subjects attributed 100% of the scene motion to self-motion. After each trial, they rated their peak %saturation on a 1-7 scale. In flight, subjects performed two trials in 0-g at specified scene speeds during a parabola followed by the same two trials in 1-g level flight. On the ground, subjects switched between supine ("0-g" analogue) and erect seated ("1-g" analogue) positions. After 2 pairs of trials, the subject reported either the posture that gave the strongest sensation of vection or else "couldn't tell". In flight, the %saturation of vection was higher (0.67 vs. 0.44) and the latency to vection onset was shorter (4.39s vs. 5.89s) in 0-g than in the 1-g trials. In the ground trials, average %saturation was higher (0.52 vs. 0.49) and latency shorter (6.02s vs. 6.51s) in the erect position compared to the supine position. All four differences were highly significantly. In post-flight trials, the %saturation was significantly higher (0.55 vs. 0.46) and latency significantly shorter (5.97s vs. 6.55s) than pre-flight. The effect of flight day was significant on the ground both on %saturation and on latency. In all test phases, the average % saturation at speed 3 was significantly greater than at speed 2, which, in turn, was significantly greater than %saturation at speed 1. As expected, the mean post-trial subjective ratings of peak saturation followed the trends in joystick indications previously described above. We found differences in ratings between 0-g and 1-g (4.3 vs. 2.9), erect trials versus supine (3.4 vs. 3.2) and post-flight trials versus pre-flight (3.6 vs. 3.2). For the subjective choice in-flight data, there was a clearly higher %saturation in 0-g vs. 1-g (0-g trials: 84%; 1-g trials: 5%). The results correspond closely to the Neurolab findings, but also indicate that the 0-g potentiation of linear vection observed after Neurolab flight day three in fact probably occurs rapidly within seconds of exposure to weightlessness. The disappearance of haptic and tactile sensations in weightlessness may play a major role in potentiating linear vection in weightlessness. (Supported by NASA contract NAS9-00097 and the CNES.)

N6.6
Relative role of visual and non-visual cues in judging the direction of 'up': experiments in the York tumbled room facility

L. R. Harris, H. L. Jenkin, R. T. Dyde, J. Kaiserman, M. R. Jenkin
Centre for Vision Research, York University, Toronto, Ont, Canada

Astronauts in microgravity frequently experience re-orientation illusions in which they or their world appear to flip and 'up' becomes arbitrarily redefined. The perception of 'up' is the result of a combination of visual and non-visual cues. Non-visual include the sense of body ("idiotropic vector") and the direction of gravity ("gravotropic vector"). Visual cues include the polarized environment as well as the polarity of individual objects and the sight of one's own and other people's bodies. On earth we are exploring the importance of visual cues that might affect the perceived direction of up. Understanding factors that affect the perception of up will enhance our understanding of perception in microgravity and may lead to countermeasures for reorientation illusions. In the absence of information about the origin of illumination (such as being able to see a table lamp) people interpret surface structure by assuming that the direction of illumination is from above. Here we exploit this phenomenon to explore the influence of the frames of reference defined by head and body orientation, gravity and visual cues on judgments of 'up'. Two sets of four grey, shaded discs were used that differed orthogonally in the polarity of their shading. One set of disks was shaded light-top, light-bottom, light-left and light-right. The second set was shaded in 30 deg steps in a 90 deg quadrant between light-top and light-left. Observers indicated with a four-button response pad which of the four discs appeared most convex and thus indicated the direction of their perceived above. 192 sets of discs were shown in a cross formation on a grey laptop screen arranged with the keyboard in the normal configuration relative to the body. Observers were positioned (i) lying on their right side in an upright room, (ii) sitting upright in an upright room, (iii) lying prone with head inverted in an upright room, or (iv) lying on their right side in a specially constructed room tilted by 90 degrees. The pattern of responses indicates that the perceived direction of 'above' is influenced by both the direction of gravity and the visual frame (defined by both the display and the surrounding room). When the room was tilted, the visual cue pulled the perceived direction of 'above' away from the direction defined by gravity. Our observations suggest that the interpretation of "up" can be influenced by particular visual cues. Interior design of spacecraft could be modified to present a preferred up direction that may reduce the incidence of visual reorientation illusions. (Supported by NSERC, CRESTech, and the Canadian Space Agency).

N6.7

Identifying head-trunk and lower limb contributions to gaze stabilization during locomotion

Mulavara P Ajitkumar[1]; Jacob J Bloomberg[2]

[1]*National Space Biomedical Research Institute, Bobby R. Alford Department of Otorhinolaryngology and Communicative Sciences, Baylor College of Medicine, Houston, TX;* [2]*Neuroscience Laboratories, NASA, Johnson Space Center, Houston, TX*

Extensive studies on the effects of short and long-duration spaceflight on human locomotor control indicate that crewmembers experience sensorimotor disturbances manifested by changes in head-trunk coordination, lower limb muscle activation patterning, kinematics and an alteration in the ability to coordinate effective landing strategies during jump tasks after spaceflight. Although impairments in the individual muscular and sensory systems have been characterized, the interactions among these systems have not yet been fully established nor systematically investigated. Stabilization of visual images on the retina during natural body movements, such as locomotion, requires coordination of the eye-head and head-trunk systems. In addition, upper body movements need to be coordinated with the lower limb to regulate the energy flow resulting from the cyclical physical impacts with the environment to prevent them from interfering with visual and vestibular sensory transduction. In order to test the general hypothesis that the whole body can serve as an *integrated* gaze stabilization system, the goal of the present study was to determine how the multiple, interdependent full-body sensorimotor subsystems respond to changes in gaze stabilization task constraints during locomotion. Nine subjects performed two gaze stabilization tasks while walking at 6.4 km/hr on a motorized treadmill: 1) focusing on a central point target; 2) reading numeral characters; both presented at 2m in front at eye level. While subjects performed the tasks we measured: temporal parameters of gait, full body sagittal plane segmental kinematics of the head, trunk, thigh, shank and foot, accelerations along the vertical axis at the head and the shank, and the vertical forces acting on the support surface. We tested the specific hypothesis that with the increased demands placed on visual acuity during the number recognition task, subjects would modify full-body segmental kinematics in order to reduce perturbations to the head in order to successfully perform the task. We found that while reading numeral characters as compared to the central point target: 1) the compensatory head pitch movement was on average 22% greater 2) the peak acceleration measured at the head was significantly reduced by an average of 13% in four of the six subjects 3) the knee joint total movement was on average 11% greater during the period from the heel strike event to the peak knee flexion event in stance phase of the gait cycle. Taken together these results provide evidence that the full body contributes to gaze stabilization during locomotion, and that its different functional elements are responsive to changes in visual task constraints. This information will enable a better understanding of the different aspects of full-body coordination that function to preserve gaze stabilization during locomotion. These data will lead to improved tests of post-flight locomotion dysfunction that will enable the effective evaluation of the efficacy of sensorimotor countermeasures used to mitigate the deleterious effects of spaceflight on locomotor control.

N6.8

Foot nystagmus: a tool for controlling spatial orientation during locomotion?

G. Melvill Jones[1], W.A. Fletcher[1], K.W. Weber[1], E.W.

Block[1], G.M. Earhart[2], F.B. Horak[2]
[1]Department of Clinical Neurosciences and Neuroscience Research Group, University of Calgary, Canada; [2]Oregon Health Sciences University, Portland OR

If one walks forward (or backwards!) around a curved trajectory and looks at one's feet, you see them performing a sequence of nystagmoid rotational movements relative to the trunk. Each foot performs a series of space-stable stance phases that 'compensate' for trunk rotation relative to space, interspersed with quick repositioning swing, or saccadic, phases in the direction of trunk rotation. The phenomenon is more clearly seen if one steps around on the spot without linear locomotion. Curiously this pattern of foot rotation closely simulates the more familiar phenomenon of Ocular Gaze Nystagmus, in which the goal is to achieve intermittent stabilization of the direction of visual regard relative to space through the summation of head rotation re space and eye rotation re head. Similarly Foot Nystagmus stabilizes the stance foot re space by summation of trunk rotation re space and foot rotation re trunk. Also similar to gaze nystagmus are the speed and consistent metrics of the 'saccades' of foot nystagmus. They can reach up to around 400-500 deg/sec during fast body rotations and exhibit very high angular accelerations during transitions from slow to quick phases, and vice versa. The question arises, are the stance phases simply stabilized by frictional contact with the ground? Apparently not, since they can be, and often are, stabilized prior to foot contact. Indeed there may occasionally be brief instances of space stabilization in mid-saccadic swing, when the foot is out of ground contact. In this communication we illustrate the phenomenon of foot nystagmus by demonstrations, video movie and digital records of foot and trunk rotation relative to space (search coils) as well as their difference (foot re trunk), together with the moments of stance foot contact and release (foot switches and microphone). These are shown both while stepping naturally around on firm ground and during space stabilized stepping over the center of a horizontally rotating turntable. The functional role of foot nystagmus is discussed in the context of spatial orientation during normal locomotion and its possible perturbation in the returning astronaut. (Supported by Canadian Institute of Health Research Grant # MA-15639 and US National Institute for Health, Grant DC-04082)

N7.1
An adaptable neural interface: the key to successful encounters of the environmental kind?
Geoffrey Melvill Jones
Health Sciences Centre, University of Calgary, Alberta, Canada

When some 50 years ago my wife presented us with our firstborn, to her dismay my first action was to turn the baby around in the delivery room, while watching its eyes. And behold! The perfect manifestation of a neonatal VOR in all its 3-D glory. Or was it perfect? We now know that although our reflex system is of course genetically endowed with the necessary central neural networks, it needs a meaningful behavioral encounter with the environment to 'learn' how to 'behave properly'. In this talk we will first explore the vast body of experimental work that has been, and still is, progressively unfolding the mysteries of how this elementary form of learning is accomplished in vestibular sensory-motor and perceptual systems. From here we turn to experimental evidence suggesting the need for analogous adaptive tuning in basic somatic sensory-motor systems such as those responsible for the precision control of locomotion and the curvature of its trajectory. To conclude, we arrive at a general inference that behavioral access to the adaptive neural interface constitutes an essential element in both the establishment and maintenance of normality in our dynamic relationship with the prevailing physical world in which we live.

N7.3
Sensory-motor balance control deficits following space flight
William H. Paloski
NASA/Johnson Space Center, Houston, TX

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 sensori-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 visuo-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.

Today postflight decrements in sensory-motor control have been well characterized from both basic science and occupational health perspectives. Early after flight postural stability is disrupted in all crewmembers. The underlying cause appears to be vestibular system adaptation during short duration missions, but as mission duration increases somatosensory/motor control system adaptation begins to play an important role. The exact 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 system problems. For example, orthostatic hypotension, which can exacerbate the balance control deficits, may result in part from vestibular autonomic system alterations.

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.

N7.4

Adaptation to artificial gravity

James R. Lackner, Paul DiZio
Ashton Graybiel Spatial Orientation Laboratory, Brandeis University, Waltham, MA

Prolonged exposure to weightlessness causes muscle atrophy, bone demineralization, cardiac deconditioning, central nervous system reorganizations and altered sensory-motor control. In-flight countermeasures involving body loading and exercise have been ineffective in preventing these changes. Artificial gravity created by rotating a space vehicle or a large chamber within a vehicle could be used to prevent adverse skeletomuscular, cardiac, and central nervous system changes. Pioneering studies in the 1960s pointed to 3 rpm as a possible upper limit for rotational velocity because motion sickness, fatigue, and disruptions of movement control and orientation tended to persist at higher rates of rotation owing to the Coriolis forces generated by body movements. Such a low limit would require a prohibitively large vehicle in order to generate a centripetal force level of 1 g. Our recent studies demonstrate, however, that by using appropriate adaptation schedules it is possible to adapt arm, head, and leg movement control up to 10 rpm (60°/s) and even higher, permitting the use of a much smaller vehicle. These studies also demonstrate that exposure to Coriolis forces is a normal consequence of body movements in our natural Earth environment. During voluntary turning and reaching movements on Earth, high torso velocities are attained (e.g. 150°-200°/s) and large Coriolis forces are generated on the arm, yet no movement errors occur. Thus, it is not surprising that humans also have the capacity to adapt to high rotation rates in artificial gravity environments. (Supported by NASA grant NAG9-1263.)

N7.5

Adaptation to vertiginous vestibular stimulation

Mingjia Dai[1,2], Theodore Raphan[1,3], Bernard Cohen[1,2]
[1]Department of Neurology, Mount Sinai School of Medicine, NY, NY; [2]Department of Physiology and Biophysics, Mount Sinai School of Medicine, NY, NY; [3]Department of Computer and Information Science, CUNY, NY, NY

Artificial gravity produced by constant velocity centrifugation has been proposed as a countermeasure for the adverse effects of prolonged exposure to microgravity. Unavoidably, however, any head movement during the centrifugation engenders two-axis rotation and produces provocative motion sickness and disorientation. In this study, we sought to investigate the time course of adaptation to the two-axis rotations with and without the anti-motion sickness drug (promethazine) and to understand the underlying mechanism of the adaptation symptoms. 16 subjects in two groups with or without promethazine were studied in a double-blind, crossover design. The subjects roll-tilted their heads about ±45° about their naso-occipital axis over one second while being rotated at a constant velocity of 138°/s about a vertical axis (RWR). The endpoint was a sense of impending vomiting. Adaptation to RWR was measured by the number of head movements that the subjects could make. Testing was done in two sessions, one month apart. Each session was comprised of four consecutive tests over four days. In contrary to the head movement paradigm, five subjects were also tested with their head fixed in a 45° roll-tilt position throughout the rotation. Horizontal and vertical eye movements were recorded by video-oculography, and the axis of eye rotation was reconstructed in two dimensions. Results: 1) The number of head movements that the subjects were able to make increased significantly over time in both the drug and placebo groups. There was no difference between the groups in the number of head movements. 2) The number of head movements was inversely correlated with the horizontal vestibular time constant. 3) The stimulus velocity of the head was deviated from gravity by the same amount but in different directions for different head roll-tilt positions. The eye rotation axis was also shifted away from gravity but in a different amount from the shift in the stimulus axis. The larger the deviation of the eye movement axis from gravity, the greater was the vertiginous sensation that the subjects reported. 5) When the head was fixed in a 45°-tilt position in which the horizontal and vertical semicircular canals were also stimulated simultaneously, the stimulus vector was not shifted away from gravity, and the subjects did not report motion sickness or disorientation. We conclude: 1) Adaptation to the vertiginous stimulation can be achieved by repetitive exposure and promethazine neither prevents nor hastens the adaptation process. 2) The dominant vestibular time constant reduces *pari passu* with the reduction in vertigo induced by RWR. 3) Motion sickness and disorientation are associated with misalignment of the axis of eye velocity from gravity. This misalignment may provide a reference for assessing both subjective orientation and the potential for producing motion sickness. (Supported by NSBRI NCC 9-58-25)

N7.6

Effect of repeated long-duration exposures to a virtual environment on simulator sickness and postural disturbance

H.B.L. Duh[1,2], M.Lahav[3], D.L. Harm[1], D.E. Parker[2,3], L.C. Taylor[4]

[1]Neuroscience Laboratory, NASA Johnson Space Center, Houston, TX; [2]Department of Otolaryngology, University of Washington, Seattle, WA; [3]Human Interface Technology Laboratory, University of Washington, Seattle, WA; [4]Wyle Laboratories, Houston, TX

Simulator Sickness (SS) is a major side effect of simulator and virtual environment (VE) training. Research is needed to determine the optimal length of single exposure and the optimal inter-session interval to enhance VE training. Postural instability appears to be a precursor of SS. Therefore, it may be appropriate to include measures of postural instability as a dependent variable in preliminary studies. This study investigated the effects of repeated long-duration immersive VE exposures on SS and postural stability during four different stances. Ten subjects were exposed to a virtual environment presented on the VR4 head-mounted display (HMD). They navigated in the virtual environment for one hour Simulator Sickness Questionnaire and postural stability was examined during 4 different stance conditions: (1) eyes open, sharpened Rhomberg stance for 30 sec (2) eyes closed, sharpened Rhomberg stance for 30 sec; (3) chin-up, sharpened Rhomberg stance for 15 sec and (4) eyes closed, preferred one –leg stance for 10 sec. Center of balance (COB) dispersions were calculated for each trial. The procedure was repeated at 24 and 48 hours. Subjects reported significantly more severe SS symptoms immediately after the first day VE exposure relative to the second and third days. There was a large, statistically significant effect of stance condition: the more "unstable" stance conditions were associated with larger COB dispersion. The data suggest that on successive days, pre-VE exposure postural disturbance tended to increase except for eyes-closed, one-leg stance condition. Except for the eyes closed one-leg stance condition, post-exposure instability tended to increase on the second day and decrease on the third day. Pre- versus post-exposure differences tended to be lower on the third relative to the second day except for eyes-closed, one-leg stance. SS decreased significantly following the second and third day exposures relative to the first day. Regarding postural stability, large response differences across individuals limit our ability to draw firm conclusions. In general, pre-exposure postural instability tended to increase slightly across days. However, both post-exposure and pre- versus post-exposure differences tended to decrease on the third relative to the second day. These results are consistent with a sensory-motor adaptation explanation. They suggest that SS and postural instability associated with long-duration VE exposure is likely to decrease with repetitions. (Supported by NASA Grants NC 9-56 and NRA-98-HEDS-02).

N7.7

Gravity and perceptual stability during head movement

P. Jaekl, M. Jenkin, J. Zacher, L.R. Harris

Centre for Vision Research, York University, Toronto, Ont, Canada

The perceptual world normally remains stable during voluntary head movement. Oscillopsia, or loss of this perceptual stability, can be very disorienting and might contribute to discomfort making head movements in unusual environments such as microgravity. Translation and rotation components of self motion are detected by different patterns of optic flow and by different divisions of the vestibular system. A given movement can involve different sensors depending on the orientation of the movement with respect to gravity. For example yaw rotation while sitting upright does not involve a change in orientation relative to gravity but does when supine. Similarly translation along the dorsal-lateral axis of the head adds and subtracts from gravity when standing up but not when supine. Might gravity contribute to this sensation of stability? To achieve perceptual stability requires knowing about the movement, especially about the movement of the eyes in space; predicting the expected visual movement of the world and comparing the actual and expected movements. We measured how much the visual world could be moved during various head rotations and translations and still be perceived as visually stable. We looked for differences in performance that might correspond to an effect of gravity during a given movement. Our subjects' task was to distinguish self produced visual motion from external visual motion during rotation around the yaw, pitch and roll axes and during translation in the naso-occipital, inter-aural and dorsal-ventral directions. The axis or direction of motion was arranged to be parallel or orthogonal to the direction of gravity. Subjects wore a head-mounted display that was updated in response to head movement, monitored by a mechanical tracker. The ratio between head and image motion was varied. Subjects indicated whether the display appeared earth-stationary (perceptually stable) or appeared to move relative to the ground. For both rotation and translation there was a large range of ratios of visual motion to head motion that was tolerated as perceptually stable. The ratio most likely to be accepted as stable corresponded to visual motion faster than head motion. For rotation there were no consistent differences between yaw, pitch or roll axes and the orientation of the axis relative to gravity also had no effect. For translation, motion in the naso-occipital direction was on average matched with less visual motion than inter-aural or dorsal-ventral motion but again the relationship between the directions of motion and gravity had no effect. There were no differences in judgments of perceptual stability performance that depended on whether the head motion was accompanied by changes of the head's orientation with respect to gravity. This implies a relatively small role of gravity in the perceptual response to active head movement. (Supported by NSBRI, the Centre for Research in Earth and Space Technology, NSERC, and the Canadian Space Agency).

N7.8

Vertical skew due to varying gravitoinertial forces: a possible consequence of otolith asymmetry

F Karmali, S Ramat, M Shelhamer
Johns Hopkins University School of Medicine, Baltimore, MD

The otolith asymmetry hypothesis (von Baumgarten, Life Sci Space Res 1979;17:161-70) suggests that differences between left and right otoliths are normally compensated for in the 1-g field of earth. Under varying gravitoinertial forces (GIF), this compensation may be inappropriate, leading to incorrect eye movements and visual perceptions. For example, disconjugate ocular counterroll (OCR) has been found under varying GIFs in parabolic flight (Diamond and Markham, J Vestib Res. 1993;3:289-95) and centrifugation (von Baumgarten, Acta Astronaut 1990;21:519-25). During parabolic flights, we observed that an eccentric target viewed binocularly in darkness seemed to split into two targets that diverged vertically. The level of divergence seemed related to instantaneous GIF. The diverged images were difficult to fuse, especially during g-transitions. Since the target was foveated, asymmetric OCR cannot explain this divergence. We suggest the divergence is due to vertical ocular skew, which has not been seen before during such GIF transitions. Eye movements were recorded with a binocular video system. During parabolic flight, subjects fixated a target 25° to the right, in darkness. Since the observation of this effect was unexpected and made in the course of other experiments, few trials (parabolas) of data are available. Seven trials were analyzed from five subjects. Eye movement records show a change in vertical ocular alignment between the 0-g and 1.8-g phases of flight. Alignment is relatively constant within a given GIF level. Across all trials, there is a mean difference, between 0-g and 1.8-g, in vertical alignment of 1.25±1.03°; the difference is significant in 6 of 7 trials (*t*-test, $p<0.001$). During the transition from 1.8-g to 0-g, the relationship between difference in vertical eye position and GIF is approximately linear, with a significantly non-zero slope in 5 of 7 trials (*t*-test, $p<0.001$). The results provide evidence for vertical skew related to GIF, possibly as a consequence of otolith asymmetry. There are significant implications for performance of critical tasks during periods of rapid g-transition (e.g., shuttle reentry). An open question is whether the skew is most dramatic during actual GIF changes; some subjects in flight perceived larger deviations during the g-transitions. We are performing follow-up studies, using linear translation or eccentric rotation to impose acceleration along the z-axis of the head, while subjects observe a visual target. Initial trials suggest that g-transitions are critical, since there is perceived divergence during rapidly-changing GIF in the sled, but not in the chair where GIF is more constant. Another avenue we are pursuing is the Lancaster red-green test during short, active vertical head translations. Preliminary results suggest that skew is orbital-position dependent, occurring in opposite directions depending on whether the subject is looking left or right. Clinically, this is referred to as an alternating non-concomitant skew deviation. (Supported by NSERC (Canada), NIH DC02849, NASA/NSBRI)

N8.1

Post-spaceflight orthostatic intolerance: possible relationship to microgravity-induced plasticity in the vestibular system

B.J. Yates
Dept. Otolaryngology, Univ. Pittsburgh School Medicine, Pittsburgh, PA

Even after short spaceflights, most astronauts experience at least some postflight reduction of orthostatic tolerance; this problem is severe in some subjects. Recent studies, which are discussed below, have demonstrated that signals from vestibular otolith organs play an important role in regulating blood pressure during changes in posture in a 1-g environment. Because spaceflight results in plastic changes in the vestibular otolith organs and in the processing of inputs from otolith receptors, it is possible that a contributing factor to postflight orthostatic hypotension is alterations in the gain of vestibular influences on cardiovascular control. One line of evidence showing that vestibular signals influence cardiovascular regulation comes from experiments in which labyrinthine afferents were selectively stimulated. Electrical stimulation of the vestibular nerves or head rotations in animals with extensive denervations to remove nonlabyrinthine inputs produced by the movement result in an increase in sympathetic nervous system activity and blood pressure. Only those sympathetic efferents that influence vascular smooth muscle, and not those that innervate targets such as gastrointestinal smooth muscle, respond to stimulation of the vestibular nerve. Furthermore, vestibular stimulation often elicits reciprocal changes in activity of sympathetic efferents innervating blood vessels in the upper body and lower body and opposite hemodynamic responses in forelimb and hindlimb blood vessels. This work cumulatively indicates that the vestibular system provides complex, patterned influences on sympathetic nervous system outflow, and does not simply elicit nonspecific autonomic responses. Other evidence showing that the vestibular system participates in cardiovascular regulation comes from studies in which labyrinthine inputs were removed and the effects of these lesions on orthostatic tolerance were assessed. Elimination of vestibular inputs diminishes the ability of an awake animal to rapidly adjust blood pressure during postural alterations. Effects of vestibular lesions on cardiovascular regulation are exacerbated by ablation of a specific region of the vestibulo-cerebellum: the uvula. These observations show that labyrinthine inputs participate in cardiovascular regulation during normal physiological conditions. In summary, considerable evidence suggests that inputs from vestibular otolith organs participate in eliciting changes in sympathetic nervous system activity during movement and changes in posture that are important for the maintenance of stable blood pressure in a 1-g environment. Removal of vestibular inputs compromises the ability to correct blood pressure during movement, and thus, increases susceptibility for orthostatic hypotension. It is also well established that exposure to unusual gravitational environments results in morphological changes in vestibular otolith organs and adaptation in the processing of signals from these endorgans. Thus, post-spaceflight orthostatic intolerance may stem in part from plastic changes that occur in the vestibular system during exposure to microgravity. Preliminary studies have supported this hypothesis, which now requires more thorough testing to be validated. (Supported by NIH grant R01 DC00693.)

N8.2

Changes in g help define the otolith system

Charles H. Markham, Shirley G. Diamond
University of California, Santa Barbara

Knowledge of the pathophysiology of the otolith system and its treatment in disease states has lagged behind studies of the semi-circular canals. This is partly because there have been fewer ways to stimulate and to record responses in the otolith system. Using ocular torsion as a window, carefully excluding any canal stimulation, and subjecting the otoliths to various novel stimuli helps us to better understand the otolith system. We shall present data under three experimental situations: (1) the hyper- and hypo-stimulation of the otoliths produced in parabolic flight, (2) the novel absence of stimulation during prolonged spaceflight and (3) static and dynamic stimulation on earth, the former which we shall present as being the novel, less functional system. Regarding (1) above, we shall demonstrate the characteristic abnormal torsional eye movements induced by parabolic flight. We found the patterns of eye torsion effectively discriminated between astronauts who had experienced space motion sickness (SMS) and those who had not. We shall offer the explanation that this is due to decompensation of structurally and/or functionally asymmetric utricles. Parabolic flight also leads to over-stimulation of otoliths, which may produce motion sickness similar to boat and car motion sickness but a different entity than SMS. Regarding (2) above, long-term spaceflight leads to severe hypo-stimulation of the otoliths, in turn leading to random, apparently uncompensated torsional eye movements. Further, on return to Earth, abnormalities persist for weeks to months. In (3) above, we find static head tilts in multiple positions lead to increased ocular torsional abnormality and disconjugacy compared to ocular counterrolling with dynamic stimulation. We suggest the explanation lies in the findings that patches of the otolith move independently, i.e. the otolith membrane does not move *en bloc.* Additionally, it has been shown that otolith hair cells are enhanced by active bending of the hairs compared to a constant deflection. There is a close analogy between the novel, constant hypostimulation in space and the constant hair cell deflections seen in the static condition.

N8.4

Role of vestibular system in cerebrovascular response to parabolic flight

J.M. Serrador[1], S.J. Wood[2], T.D. Wilson[3], T.T. Schlegel[4]
[1]Harvard Medical School, Boston, MA; [2]Naval Aerospace Medical Research Laboratory, Pensacola, FL; [3]The University of Western Ontario, London, Ontario, Canada; [4]NASA Johnson Space Center, Houston, TX

There is evidence that the vestibular system plays a role in cardiovascular adjustments to changes in posture. However, the role that the vestibular system plays in

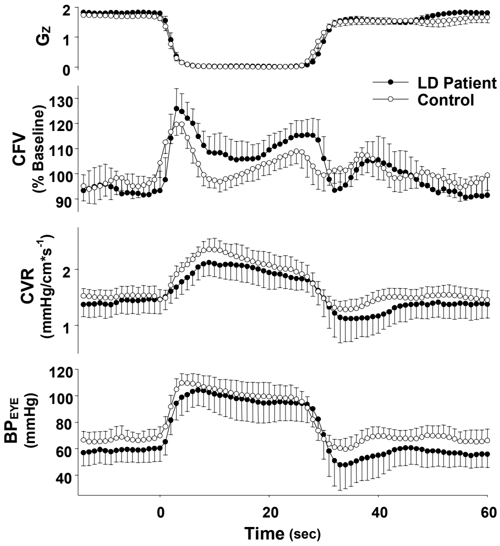

Figure – Average response of 20 parabolas in LD patient and healthy control. Values represent means±SD.

cerebrovascular adjustments to both postural and gravitational changes is poorly understood. Parabolic flight provides a unique model in which short-term exposures to hyper- and microgravity have rapid affects on both cardiovascular and cerebrovascular dynamics while stimulating vestibular organs. To examine the role of vestibular inputs in cerebrovascular adjustments to changing gravitational states, we measured cerebral blood flow velocity in a labyrinthine deficient (LD) patient and a healthy control during parabolic flight. Subjects flew 32 parabolas in NASA's KC-135 aircraft. The volunteers were restrained at the waist in the seated position and were instructed to avoid head movements while focusing on a computer monitor in front of them. An accelerometer inside the aircraft verified that single parabolas consisted of a 20-25 s period of microgravity (approximately 0.01 G_z) preceded and followed by 20-25 s pull-up and pull-out phases of hypergravity (up to +1.8 G_z), respectively. Throughout the flight cerebral blood flow velocity (CFV) was measured by trasncranial Doppler, arterial pressure by finger cuff (Portapres), heart rate by electrocardiagram and end-tidal CO_2 by nasal cannula sampling gas from expired breaths (Puritan-Bennet).

Blood pressure at eye level (BP_{EYE}) was calculated from mean arterial pressure minus hydrostatic gradient. Cerebral vascular resistance (CVR) was calculated as BP_{EYE}/CFV. Beat-by-beat data were interpolated to 1 Hz and averaged across parabolas in which complete sets of data were available (20 parabolas for each subject). Upon transition from hypergravity to microgravity, the LD patient and healthy subject demonstrated similar changes in BP_{EYE} and CFV (Figure). Specifically, BP_{EYE} increased due to the removal of the gravitationally-induced hydrostatic gradient resulting in an immediate increase in CFV in both the LD patient and healthy control. Interestingly, in the healthy control with intact vestibular organs, CFV returned to baseline levels within 10 seconds, suggesting normal cerebral autoregulation, whereas CFV in the LD patient failed to return to baseline levels due to an inadequate increase in CVR, potentially suggesting impaired autoregulation. The LD patient also demonstrated a relatively blunted heart rate response (not shown). Changes in end-tidal CO_2 were similar in both subjects with a gradual increase throughout microgravity. These data suggest that an intact vestibular system may be important for maintaining cerebral blood flow during changing gravitational states. In particular, the lack of vestibular inputs in the LD patient may have related in some way to a failure of CFV to return to baseline levels during parabolic microgravity. A role for vestibular inputs in cerebrovascular regulation is therefore suggested by these data, but requires further study for verification. (Supported by NSERC, NASA and NIH/NIDCD R03-DC05547)

N8.5

The role of "extra-vestibular" inputs in maintaining spatial orientation

Michael E. Hoffer[1], Kim Gottshall[1], Peter Weisskopf[1], Robert J. Moore[1], Richard D. Kopke[1], Derin Wester[1], Carey Balaban[2]

[1]Department of Defense Spatial Orientation Center, Naval Medical Center San Diego; [2]Department of Otolaryngology, University of Pittsburgh, Pittsburgh, PA

An individual's sense of spatial orientation is commonly attributed to be derived from visual, vestibular, and proprioceptive inputs. Spatial disorientation is often ascribed to arise from a conflict between one or all of these three systems. However, relying on this well studied view of spatial perception has not totally explained motion intolerance and spatial disorientation. It is likely that more than these three systems are involved in spatial orientation. This paper examines how cues obtained from posture, respiration, and blood flow contribute to spatial orientation. Disordered regulation of any of these factors can be identified in land based tests and allows us to study pre-disposing factors to motion sickness. In addition, examining these factors in motion environments allows us to study the mechanisms involved in motion intolerance. Postural studies were obtained in a cohort of individuals experiencing motion sickness in a variety of military environments. A definite pattern of altered postural control on land was demonstrated in over seventy percent of these individuals. The predictive value of this test and refinement of the test for increased accuracy as a pre-screening method are examined in this report. A second cohort of individuals was examined while underway in a United States Navy ship. Respiratory and postural measurements were performed on 3 motion sick and three non-motion sick individuals within 24 hours of going to sea as well as 48 hours after the first measurement. Initial postural and respiratory adaptations were compared to ship motion and the strategies of individuals without motion sickness were compared to the strategies of the motion sick individuals. Adaptive patterns were examined in each group and found to be complete within 48 hours. The implications of these findings are examined in developing strategies to deal with spatial disorientation in a number of settings. These implications lead us to propose that non-traditional vestibular inputs exist throughout the body that are important for spatial orientation in motion environments. Defining these extravestibular inputs represents a paradigm shift in balance theory and may provide us with new targets on which to focus as we explore the challenge of balance in space.

N8.6

Motion trajectory prediction cues alleviated simulator sickness during passive travel though a virtual environment

J.J.W.Lin[1], H.Abi-Rached[1], T.A.Furness, D.E.Parker[2]

[1]Human Interface Technology Laboratory; [2]Department of Otolaryngology, University of Washington, Seattle, WA

This study investigated cues that permit prediction of turns during passive movement through a virtual environment (VE). Effects on presence, enjoyment, and simulator sickness (SS) were examined. Previous research indicated that the ability to predict turns while driving reduced motion sickness. For passengers, prediction is based on seeing the road ahead of the car. Unexpected results from a preliminary study led to the following questions. Do cues that permit prediction of turns influence subjects' responses to presence / enjoyment / SS scales? Does awareness of cues influence subjects' responses? 12 subjects were exposed to complex motion through a cartoon-like simulated environment in a driving simulator. The simulator included a full-size car, 3 video projectors, and 3 230 x 175 cm screens. Each subject was exposed to each of 3 conditions for 2-min using a counterbalanced experimental design. Forward velocity was constant and the motion trajectory was the same across all conditions. In Condition 1, a green path through the simulation provided detailed cues for turns. In Condition 2 (simplified cues), the trajectory followed a green path that was drawn like a polygonal sidewalk. For Condition 3 (no turns cues), the green path was rotated 90° relative to the VE scene, but the trajectory was the same as in the previous conditions. Following each trial, subjects completed the Revised Simulator Sickness Questionnaire, a Presence / Enjoyment Questionnaire, and a Trajectory "Smoothness" scale. They were asked to report their awareness of the path after completing all conditions. SS in the no-cue condition were significantly higher than in the simplified-cue condition. Contrary to expectations, SS for the simplified-cue condition was slightly lower than for the detailed-cue condition. Subjects' responses on the presence and enjoyment scales were not different across the different levels of prediction cues. Although some reported noticing "different colors of grass" (the path was a darker green than the VE grass) none of the subjects reported distinguishable differences across Conditions 1-3. None reported recognizing that their motion through the VE followed a path. However, subjects reported, at a marginally significant level ($p = .052$), that the car motion was smoother for the detailed-cue than for the no-cue condition. Finally, there was a somewhat surprising and statistically significant difference in the mean ranks of the post-experiment, subjectively reported abilities to predict turns, which, from high to low, were Conditions 1, 2, and 3, respectively. Unobtrusive and unreported motion cues appeared to alleviate SS in a VE. This could be useful for VE training that requires trainees to attend to a task. The results from this study can be discussed in terms of the efferent copy / prediction models developed by von Holst, Mittelstaedt, Sperry and others. Unobtrusive motion trajectory cues for passive observers are among the interventions to alleviate SS in motion simulators and VEs being pursued at the Human Interface Technology Laboratory. (Supported by Eastman Kodak, Inc. and NASA Grant NCC 9-56.)

N9.3

Review of countermeasures for spatial orientation disturbances and space motion sickness in the U.S. and Russian space programs

Deborah L. Harm
NASA Johnson Space Center, Houston, TX 77058

Most astronauts and cosmonauts experience a variety of spatial orientation and perceptual disturbances on orbit and upon return to earth. Space motion sickness (SMS) has been reported by 48% of the cosmonauts in the Russian space program and by approximately 80% of U.S astronauts; 94% of the cosmonauts experience reentry sickness following long duration missions. During adaptation to microgravity and readaptation to Earth, altered relationships among the sensory modalities lead to a wide variety of orientation and perceptual disturbances. These disturbances include position illusions such as inversion, difficulty determining subjective vertical, self and surround motion illusions, and disturbances in pointing and recognition of limb position. A wide variety of countermeasures for orientation disturbances and/or SMS have been tested but have had only limited success. These countermeasures include anti-motion sickness medications, behavioral techniques such as limiting head movements and maintaining an Earth vertical orientation, mechanical devices, biofeedback training, and preflight training. Preflight vestibular training in the Russian space program has primarily involved repeated exposures to Coriolis (cross-coupled angular) acceleration; however, this method does not duplicate the sensory stimulus conditions encountered in weightlessness. In the U.S program two part-task training devices have been designed to preadapt astronauts to sensory stimulus rearrangements similar to those encountered in microgravity. This preflight adaptation training (PAT) is based on the following postulates: 1) microgravity is a form of sensory stimulus rearrangement to which astronauts adapt (sensory conflict theory); 2) adaptation may result from sensory compensation and/or reinterpretation; and, 3) because the central nervous system is "plastic", people can learn and store perceptual, sensory and sensory-motor responses appropriate to different sensory stimulus conditions and they can learn to invoke these alternative responses almost immediately when the conditions change; i.e., they develop "dual-adapted" states. The purpose of this training is to demonstrate sensory phenomena likely to be experienced inflight and immediately postflight, alter sensory-motor reflexes, and eliminate or reduce SMS and orientation and motion disturbances. The two devices were used in a space flight investigation designed to assess perceptual responses to voluntary head movements. The findings from this investigation indicated that several of the stimulus rearrangement conditions in both devices produce perceptual experiences quite similar to those associated with space flight. . Moreover, crewmembers that participated in this study, which included education in functional anatomy of the vestibular system, perceptual processes, and demonstrations and experience with illusory phenomena, show an average 33.5% improvement in SMS symptoms compared to a group of astronauts who did not participate in the investigation.

N9.4

Update on the status of rehabilitative countermeasures

Helen S. Cohen
Bobby R. Alford Department of Otorhinolaryngology and Communicative Sciences, Baylor College of Medicine, Houston, TX

Rehabilitation professionals, i.e., therapists, use multidimensional approaches, particularly for complex, multifactorial problems. These approaches include active exercise for muscle strengthening, adaptive equipment and environmental modifications for safety and task facilitation, specific skill training for essential tasks, and active participation in purposeful activities designed around the parameters of interest for more generalized motor learning for performance in novel situations. This time-honored approach has been effective for treating many problems for more than 100 years.

The effort to develop rehabilitative countermeasures to ameliorate the effects of long-term exposure to microgravity, which causes multifactorial problems, should take a similar, multidimensional, approach. Vestibular scientists must develop countermeasures to the known and anticipated motor control problems because of the system's broad influence in sensorimotor skill. After many years of work on the problem, however, we have made little progress toward developing operational countermeasures.

This problem has arisen for several reasons. The fascinating richness and complexity of the vestibular system means that changes in the use of vestibular input are manifested in many ways, all of which should be addressed, therefore presenting a huge amount of work. Also, the multiple research funding mechanisms, and the different mandates of those institutions, means that investigators working in the same field, but on unrelated grants, do not necessarily coordinate their work. Finally, we have a personnel problem. Relatively few scientists work in this area. This group includes engineers, physiologists and physicians with expertise in basic and clinical vestibular science, many of whom have had far-reaching influence on neuroscience and medicine, but the actual number of people is small. The group of investigators and physicians who routinely deal with the functional problems of astronauts and the limitations of working in the space environment is tiny; the number of investigators who are therapists and have real expertise in the development of rehabilitation programs is miniscule. That's the bad news.

The good news is that we are little but mighty. The modest size of our community can be an advantage. The entire group can decide to take a more coordinated, collaborative approach than investigators in other, larger fields have used. Also, by fortunate happenstance, individual research groups have begun approaching different rehabilitative aspects of this problem. The MIT/ Mt Sinai group is planning studies of the short-arm centrifuge and active head movements. Several groups are exploring the influence of visual/ spatial effects in the environment. The Naval Aerospace Medical Research Laboratory is developing the vibrotactile vest, which has great potential as a wearable adaptive device. The Johns Hopkins group is studying context-specific adaptation. The NASA-JSC/ Baylor lab is now studying motor learning approaches to generalized motor learning and sensorimotor adaptation. Finally, we can benefit from consultation and guidance from our Russian colleagues, who have years of experience with intervention strategies for cosmonauts. If we use this symposium to begin a greater effort toward a coordinated, multifactorial approach, guided by rehabilitation concepts, we will be able to provided appropriate countermeasures in time for a manned mission to Mars. Supported by NIH grant DC04167.

N9.5

Contextual adaptation as a spaceflight neurovestibular countermeasure

Mark Shelhamer

Johns Hopkins University School of Medicine, Baltimore MD

The phenomenon of "flashbacks" in returning astronauts suggests that some aspects of adaptation to space may be retained for days or weeks after return to earth, to be recalled with some appropriate sensorimotor trigger. This is a form of context-specificity: different adapted states are associated with different states of a context cue (e.g., gravity), and a change in the context state triggers a change in some related response. We performed several studies on context-specific adaptation of saccades and the linear VOR. Our overall goal was to assess the efficacy of different context cues in switching between adapted states. A standard double-step paradigm was used to adapt saccade gain. In each experiment, we asked for a simultaneous gain decrease in one context state and gain increase in another context state, and then determined if a change in the state would invoke switching between the adapted saccade gains. In a typical paradigm, 19 saccades were presented in one context state, and 19 saccades in the other state, and this cycle was repeated 20 times (380 saccades each context). Test trials before and after adaptation, in the two states, assessed whether each adapted gain had become associated with each state. Horizontal eye position works well as a context cue: saccades with the eyes to the right can be made to have higher gains while saccades with the eyes to the left have lower gains. Vertical eye position is less effective. Roll tilt of the head, and upright versus supine orientations, are somewhat effective in context switching. Subsequent investigations showed that a motor cue (saccade direction) is more effective than a sensory cue (head roll-tilt) in switching between adapted states. The sensory+motor combination is no more effective than the motor cue alone. An additional study demonstrated that context-specificity is effective if two different gain decreases or increases are called for, as opposed to an increase versus a decrease as in the foregoing studies. This is significant because the dynamics of gain-increase and gain-decrease adaptations are different, and context-specificity could simply be an epiphenomenon of different adaptive mechanisms for gain increase and decrease. Parallel work on adaptation of the LVOR was also carried out. Subjects were translated (0.7 Hz, 0.3 g) while asking for a gain increase or decrease. Two context cues were tested: head pitch (26°) and head roll (26° or 45°). Roll worked well as a context cue: with right roll the LVOR could be made to have a higher gain than with left roll. Pitch was less effective. Finally, saccade adaptation was performed during parabolic flight (alternating 0g and 1.8g). Different saccade gains could be associated with each gravity level, and context-specificity accumulated over the course of consecutive flights, despite intervening 1g exposure. The saccade and LVOR results both suggest that the more closely related a context cue is to the response being adapted, the more effective it is. The efficacy of motor cues indicates that interaction with the environment is more effective than passive sensory exposure.

N9.6

A concept for balance training in space - A pilot study

Lars I.E. Oddsson[1], Conrad Wall III[2]

[1]NeuroMuscular Research Center, Boston University, Boston, MA; [2]Massachusetts Eye & Ear Infirmary, Boston, MA

Astronauts lose postural control and coordination during exposure to microgravity. These problems may become hazardous and influence safety during re-entry into the atmosphere and egress of the vehicle after landing. Furthermore, astronauts have prolonged post flight balance related problems during common everyday activities such as standing, walking and turning corners. Nevertheless, current countermeasures for astronauts in space have not included exercises for postural control. We have built a 90 deg tilted room environment where subjects “stand” in a supine position while strapped to a frictionless device that allows the subject to move freely in the frontal plane, similar to when in upright standing. The device is attached to a weight stack, which provides a gravity-like force that the subject must balance against to remain “upright”. The room contains visually “polarized” objects (well defined “up” and “down”) to convey to the subject the perception of being upright in a 1-g environment. If balance training conducted in a tilted environment on earth can improve balance function during upright standing it would suggest that balance training performed in a virtual “upright” environment could be developed for use in space that would be beneficial for balance function in Martian or Earth gravitational environments. Five healthy subjects between the ages of 19 and 22 performed balance training on a wobble board in the tilted room environment on 10 occasions over a two-week period. Balance function during unipedal stance on a half-cylinder (10 trials for 35 s max) was tested in an upright position on a force platform before and after the training period. Center of pressure (COP) data were calculated and analyzed. After balance training in a 90 deg-tilted environment there was a statistically significant increase in the time subjects were able to balance on the half cylinder (mean pre-training 17.3 s, post-training 27.3 s, $p < 0.05$). In addition, there was a significant decrease in the mean velocity of the COP in the medio-lateral (31.4%) and the antero-posterior (35.6%) direction as well as in the average COP sway area per second (49.6%). Additional changes were seen in a stabilogram-diffusion analysis of the COP with a significant decrease in stochastic activity of the COP over short time intervals as well as a decrease in the transition displacement, the mean square COP displacement at the time interval when postural corrections (reversals of COP) start to dominate the COP behavior. Results from this pilot study suggest that balance training in an altered G- environment can improve balance function during upright standing. This concept should be transferable to a microgravity environment and would provide an important complement to current countermeasures focusing on cardiovascular, muscular and skeletal effects of microgravity exposure. Applications of this concept on earth would include early safe rehabilitation of balance function in bed-ridden patients.

N9.7

Pharmaceutical countermeasures for space motion sickness and their effect on the otolith and canals

F.L.Wuyts[1], G.Pauwels[1], M.Hoppenbrouwers[1], P.Van de Heyning[1], J.Dornhoffer[2]

[1]University of Antwerp, Edegem, Belgium; [2]UAMS, Little Rock, AR

A mismatch between utricular and semi-circular canal output is believed to provoke space motion sickness. To assess the utricular and the horizontal canal functions, we apply the unilateral otolith test (UOT) and the standard electronystagmographic (ENG) test battery. We use a modified paradigm of the unilateral otolith test during which the subject is rotated about an earth vertical axis at a velocity of 400 degrees per second and 4 cm translated along an interaural axis to the right and to the left. When the axis of rotation is positioned through one utricular system, only the contralateral utricle is stimulated. Consequently, the centrifuged utricle feels an outward pulling force equal to 0.4g, corresponding to a gravito-inertial acceleration (GIA) tilt of 21 degrees. This utricular stimulation induces an ocular counter rolling (OCR) that is measured on-line using validated three dimensional video-oculography. For analysis of the experimental data, we use a theoretical model proposing a linear relationship between the OCR and the GIA tilt felt by a transducer placed at the centre of the head, behind the subject: (OCR = intercept + slope x GIA tilt). The function of each utricle is assumed to be additive. The slope of the linear regression is a measure of the responsiveness of both utricles whereas the intercept is a measure of lateralization. These results are presented in the framework of a study Pharmacological countermeasures for space motion sickness (NSBRI / NASA grant: #NCC9-58), the aim of which is to assess the effect of promethazine, scopolamine, lorazepam and meclozine in healthy subjects. We present here preliminary results of the effect of these medications. Nine healthy volunteers (five female, four male) with an average age of 27.1 year (21-47 year) were recruited. All subjects had three sessions: one control session (UOT and ENG) one week prior to the intake of the drug, one session with UOT and ENG at the maximum response of the drug and one control session with UOT one week later. Wilcoxon Matched pairs signed rank test indicates a significant decline in utricular responsiveness after intake of promethazine ($p = 0.044$) in reference to the control measurements. The effect on the horizontal canal responsiveness is even stronger ($p = 0.012$ for the caloric sum and $p=0.012$ for the gain on rotation). Scopolamine however, has no significant effect on the utricular responsiveness ($p = 0.16$). The effect on caloric sum and gain are however significant ($p=0.012$ each). Similar results will be presented at the meeting for meclozine and lorazepam. Our results indicate that intake of promethazine leads to a suppression of the utricular function, a declined responsiveness of the horizontal semicircular canals and also to central inhibition. On the other hand, scopolamine does not reduce the utricular sensitivity, although it induces central inhibition as well as a significant decline in horizontal semicircular canal function.

NP1.1

Chlorpheniramine for motion sickness

Jay C. Buckey, Jr., Donna Alvarenga, Bernard Cole, James R. Rigas

Department of Medicine, Dartmouth Medical School, One Medical Center Dr., Lebanon, NH

Motion sickness remains a significant problem for those involved in naval, aviation and space operations. Most motion sickness remedies are also sedating, making them undesirable in operational settings. We studied chlorpheniramine as a potential motion sickness treatment. Dose-ranging trials were performed to establish the most effective dose and the drug's effects on cognition. Eighteen normal subjects received placebo, low dose (4 mg) or high dose (12 mg) chlorpheniramine 3.5 hours before off-axis vertical rotation. Cognitive testing included a battery of objective and subjective tests performed before drug ingestion, at peak drug effect and following rotation. Both low-dose and high-dose chlorpheniramine significantly increased the time in the chair compared to placebo [high dose 7.2 minutes to 11.7 minutes, p=0.001]. Chlorpheniramine did not affect performance on objective cognitive tests. Subjects reported significantly more sleepiness and less alertness with high-dose chlorpheniramine. Chlorpheniramine is effective and could be considered for use against motion sickness. Chlorpheniramine is less sedating than other antihistamines used for treating motion sickness. It can be administered by a variety of different routes, which could offer operational flexibility.

NP1.2

Effects of histamine depletion on acute responses of rats to 2G

Patrick M. Fuller

Section of Neurobiology, Physiology & Behavior, University of California, Davis, CA

Exposure to altered force environments has profound affects on the physiology of organisms. Utilizing the head tilt (*het*) mouse model, we previously demonstrated a novel role for the vestibular system, specifically the maculae organs, in transducing the ambient force environment (+G) and largely mediating the acute feeding, body mass, body temperature and circadian rhythms response to +G. The question remains, however, what CNS neurotransmitter system(s) are involved in the central processing of these responses. Because histamine and its receptors are found in the vestibular complexes, the possibility exists that the CNS histaminergic system may play a role in the regulation of these vestibular mediated responses. If the histaminergic system were involved in the acute body temperature response of rats to 2G, we would predict that mice centrally depleted of histamine will have an altered physiological response to 2G exposure. We tested such a hypothesis by administering i.p. injections (100mg/kg) of alpha-fluoromethylhistidine, a specific inhibitor of histidine decarboxylase, to centrally deplete 5 mice of histamine and comparing the body temperature response to 24 hours of 2G exposure of these mice to 5 saline-injected control mice. Body temperature was recorded via i.p. implanted biotelemetry units. The initial acute drop in body temperature of the control mice was similar to that seen in previous studies (ca. 6°C), however, the drop in body temperature was significantly larger (ca. 10°C) in the histamine-depleted mice. Moreover, the histamine-depleted mice evidenced a highly attenuated rate of recovery of body temperature. These results suggest that the vestibular system may influence the body temperature response to 2G via the histaminergic system.

NP1.3

Postural responses increase complexity with visual-vestibular discordance

E.A. Keshner[1], R.V. Kenyon[2]

[1]*Sensory Motor Performance Program, Rehabilitation Institute of Chicago and Department of Physical Medicine and Rehabilitation, Feinberg School of Medicine, Northwestern University, Chicago IL;* [2]*Department of Computer Science, University of Illinois at Chicago, Chicago IL*

The perception of self-motion can be due to either vestibular or visual signals or both. Results from recent PET and MRI studies of cortical visual and vestibular sites (Brandt et al. 2002) using constant velocity visual motion suggest that the more reliable input is more heavily weighted and conflict reduced through an inhibitory reciprocal vestibulo-visual interaction. During functional activities, however, perceptual ambiguities are prevalent and identification of the dominant input may not be as readily apparent. We have examined the postural response to simultaneous discordant inputs in order to determine whether subjects consistently select one pathway as the more dominant or reliable modality while suppressing the response to other input pathways. Seven healthy (25-31 yrs) and one labyrinthine deficient (LD) adult (34 yrs) stood on a platform that translated sinusoidally (0.25 Hz, ±10 cm) in the a-p direction for 280 sec. Then, a virtual environment produced 0.1 Hz, ±6 m sinusoidal fore-aft motion of the visual scene. Lastly, platform and scene motions were presented concurrently. Magnitude squared coherence and power of the response at each stimulus frequency were calculated. Repeated measures ANOVA and post-hoc comparisons ($p < 0.05$) were performed on area under the power curve, center of pressure, and kinematic data from the head, trunk, and lower limb. Platform motion alone produced highly coherent (~0.9) segmental responses. At first, visual scene motion alone did not elicit good coherence (~0.6). Around 180 sec, however, segmental amplitudes, power and coherence at the frequency of the visual scene increased to 0.8 which might suggest subjects were experiencing visual vection. With combined visual and platform motions there was a significant increase in the response amplitudes. Power at the visual frequency for the head and trunk was significantly greater than to either input presented alone. This increase could not be obtained by a simple summing of the response to single frequency inputs. Healthy subjects exhibited high coherence (> 0.9) to both frequencies, but although power at the visual frequency dramatically increased for the LD subject, his responses were coherent only with platform frequency. The responses that emerged in this study did not manifest a linear increase but rather a non-linear increase in magnitude accompanied by a more complex frequency spectrum. Only the labyrinthine deficient subject demonstrated frequency response characteristics that favored only one input. Thus our data suggest that responses to the convergent inputs were the result of a non-linear gain enhancement rather than a linear summation. This non-linear response would be dependent upon both stimulus agreement and stimulus context (Wall et al. 2001). We infer from these results that, in a dynamic environment, the postural system does not selectively weight a single relevant input, but that each input is accommodated by a continuous monitoring of environmental signals in order to appropriately modulate the frequency and magnitude characteristics of the response. Instability in labyrinthine deficient subjects may be due to a loss of this multi-modal monitoring. (Supported by grant DC01125 from NIH-NIDCD and AG16359 from NIH-NIA).

NP1.4
Mechanical sensitivity and growth of otoliths
Alexander V. Kondrachuk
Institute of Physics, Natl.Acad.Sci., Kiev, Ukraine

It is suggested that the change of otolith mass during the development of otolith in altered gravity conditions (AGC) as well as the growth of otoliths in fishes in normal conditions [Lychakov, 1988] is determined by the feedback between the otolith dynamics and the processes that regulate otolith growth. The hypothesis originates from an otolith pendulum model [de Vries, 1950] in which the otolith mass is a parameter. The work aims to examine validity of this hypothesis and analyze the parameters that may influence mechanical behavior of otoliths in the AGC. The hypothesis is tested by comparing a pendulum model with a simplified spatially distributed (SDP) analytic model of an otolith [Kondrachuk, 2001]. It enables us to analyze the influence of physical parameters of an otolith structure on mechanical sensitivity of an otolith. Results of the modeling are compared with experimental data from fishes and mammals. If an otolith structure allows only for parallel-plane motion of an otolith relative to macular surface, then: a) de Vries' pendulum model corresponds to a simplified SDP model of the otolith dynamics averaged over otolith thickness, if the frequencies of acceleration are much lower than natural frequencies of an otolith, i.e. when the otolith functions as accelerometer. Thus the coefficients of de Vries' model can be expressed in terms of physical parameters of otolith; b) mechanical sensitivity of an otolith with a spatially distributed fixation to macular surface does not depend on its total mass and longitudinal sizes; c) conditions of steady mechanical sensitivity of an otolith during the fish growth in normal conditions suggest that the ratios "otolith plate thickness/Young's module of gel layer" and "viscosity of gel layer/Young's module of gel layer" remain approximately constant, whereas under the altered gravity these ratios will be violated. This will result in changes of otolith structure (opposite in micro- and hyper-gravity) to keep mechanical sensitivity steady. Results of the work allow to propose the following hypotheses regarding the relationship between the otolith growth, otolith dynamics and animal size growth: 1) the growth of sensory surface of a fish otolith that accompanies the growth of fish size is a leading factor of otolith formation. The growth of otolith mass (longitudinal size) follows the growth of sensory surface; 2) the mechanics of fish otoliths and mechanisms of fish otolith formation are likely to be intermediate between those of mollusks (3-D motion of statolith and statoconia relative to statocyst surface, correlation of growth of statocyst size and statoconia (statolith) mass) and mammals (quasi2-D motion of the OM relative to macular surface, independence of otolith dynamics from otolith mass (longitudinal size), absence of otolith growth with the growth of animal size; 3) as with mollusks, the feedback that controls fish otoliths' formation may be expected to have local origin.

NP1.5
Otolith ocular counterrolling differs in static vs. dynamic stimulation
Charles H. Markham, Shirley G. Diamond
Department of Psychology, University of California, Santa Barbara, CA

In long-term space missions, we found that spontaneous eye torsion was erratic and disconjugate compared to eye movements found in the same astronauts on Earth. To approximate similar conditions in the laboratory, we reasoned that static tilt offers unchanging stimulation of the otolith organs analogous to the hypogravity of space. Nineteen subjects underwent rotation about the naso-occipital axis in both dynamic and static conditions. Dynamic rotation (changing G vector) consisted of tilt to 90° right and left at constant velocity of 3°/s at accelerations of $0.2°/s^2$. Static rotation (constant G vector) consisted of one-minute periods of steps 30°, 60°, 90°, 60° and 30° to each side. Amplitude of OCR was significantly greater in dynamic than in static rotation ($p = .0005$). Disconjugacy was more evident in static rotation, but the difference was not statistically significant. The eye movement tracings in the static positions were similar to the tracings obtained in the hypogravity of space. Static tilt presents very little stimulation to the otolith organs, similar to the relative absence of stimulation in hypogravity. Possible explanations for the disparity of OCR responses to dynamic and static conditions lie in the findings of others that the otolith membrane moves, not as a unit but in patches. Further, hair cell responses have been found to be amplified during motion as compared to static positioning. Functionally, it appears that the otolith system performs better in the more natural dynamic state than in the conditions of static tilt on earth or the hypogravity of space.

NP1.6
Variable practice to facilitate motor learning for countermeasures
Helen S. Cohen[1], Jacob J. Bloomberg[2], Ajitkumar Mulavara[3], Carrie Roller[1]
[1]Bobby R. Alford Department of Otorhinolaryngology and Communicative Sciences, Baylor College of Medicine, Houston, TX; [2]Neuroscience Laboratories, NASA/ Johnson Space Center, Houston, TX; [3]National Space Biomedical

research Institute, Baylor College of Medicine, Houston, TX

Studies in motor learning and sports training have shown that when motor practice is varied about some parameter of interest, e.g., several target distances, performers are better able to learn a new level of that parameter, e.g., a longer distance, than when they are trained with sham or single level training conditions, e.g., only one target distance. This type of practice has become known as variable practice. Using two different training paradigms, this series of experiments is testing the concept of practice variability as theoretical framework for development of potential countermeasures. A secondary goal is to develop some of the methodologies that will be used for potential countermeasures and to develop and test assessment tools. Future spaceflight studies will then apply these techniques and will test the efficacy of a specific training regimen that uses practices variability. We have varied visual input using different lenses to train subjects on two different tasks. Using a ball throwing task we have shown no age differences in developing adaptation and we have shown significantly better performance in variable practice rather than sham or blocked practice groups. Using an obstacle course paradigm we have also shown the beneficial effects of training with variable practice. These results support the use of variable practice in motor training paradigms and suggest that this approach may be valuable for the development of spaceflight countermeasures. (Supported by NIH grant DC04167 and NASA grant E120.)

NP1.7

Voluntary head movements and vestibulo-postural responses related to short spaceflight

F. Hlavacka[1], O. Dzurkova[1], L.N. Kornilova[2]
[1]Institute of Normal and Pathological Physiology, Bratislava, Slovakia; [2]Institute for Biomedical Problems, Moscow, Russia

Adaptation during flight and re-adaptation on the earth with postural instability in astronauts returning from spaceflight involve a change in sensorimotor integration of the vestibular signals from the otoliths. We tested the change of the post-spaceflight postural reaction to galvanic stimulation affecting mainly the otoliths. We also tested spatially-directed head movements before, during and after short spaceflight to investigate the time course of sensory-motor adaptation to microgravity. Postural responses to the galvanic vestibular stimulus (cosine bell shape, four intensities up to 2.1 mA, four repetitions and two polarities) were recorded from one cosmonaut before and after 8 days spaceflight on MIR station. We measured body tilts induced by galvanic stimulation with a force platform in the first day (10 hours) after landing, in second day and in fifth day. The cosmonaut also performed six cycles of voluntary head rotation in pitch, roll and yaw directions under sound command. Head movements were recorded by video camera on the third, fourth, fifth and sixth day of the spaceflight. As control conditions, the head movements were recorded before and after spaceflight. Computer analysis of video recordings after spaceflight was used for angular velocity estimation of the head movements. During the first day after flight the force platform data showed clear instability of the cosmonaut's quiet stance, which was successfully compensated in the next days of readaptation. On the first, post-landing day, our results indicated a minimal change in vestibular reaction to the galvanic stimulus but a large overshoot of body shift and postural instability when the galvanic stimulus stopped. These results reflect the influence of altered vestibular-somatosensory interaction adapted in-flight. During the first days of weightlessness the angular velocity of head movements increased. Over the next days of microgravity the velocity of head movements gradually decreased. On landing day a significant decrease of head rotation velocity was observed compared to the head movement velocity before spaceflight. Significant asymmetry in the averaged velocity for forward and backward head movements in pitch plane was observed only on third day of the microgravity period. These results showed that sensory-motor adaptation to microgravity should be monitored by the angular velocity of aimed head movements of cosmonauts. (*Supported by Slovak Grant Agency VEGA No. 2/1095/21)*

NP1.8

“Spacecraft in miniature”: a tool for the acquisition of mental representations of large environments

Jessica J. Márquez[1], Charles M. Oman[1], Andrew M. Liu[1], Andrew C. Beall[2]
[1]Massachusetts Institute of Technology, Cambridge, MA; [2]University of Santa Barbara, Santa Barbara, CA

“Spacecraft in Miniature” (SIM) is a navigational training tool for use in large virtual environments (VE) such as space station simulations where six-degree-of-freedom movement is possible. SIM extends the “Worlds In Miniature” (WIM) terrestrial navigation tool concept of Pausch et al., to three dimensions. It is designed to facilitate acquisition of a mental representation of the environment by providing the user with a miniature 3D model of the VE that includes an avatar representation of user. It also allows users to substitute model movements for potentially disorienting virtual scene rotations in the full-scale virtual environment. To date, there have been no quantitative studies of navigation performance after training with WIM-like tools. We set out to show that after training in a virtual environment using SIM, users acquire a better mental representation when required to learn a complex 3D environment than a control. We hypothesized that SIM users, like terrestrial map learners, would have better survey knowledge, and superior understanding of where modules were located and how they were oriented. They should also be more accurate and quicker to respond to locations and orientations of modules when their own orientation is changed, implying an orientation-free mental representation. On the other hand, we expected the control subjects would have better landmark and route knowledge (describing routes based on landmarks) than SIM users, since their training compelled them to rely directly on visual cues in the local environment. Two groups were trained and tested on the layout of a virtual 3D space station, composed of modules with salient landmarks and nodes. The experiment group (SIM subjects) were trained using the SIM tool while the control group only viewed the virtual environment directly, by translating and rotating within the station without the miniature model. Testing consisted of pointing to specified locations and describing, through given questions, routes to these locations in different roll orientations. Ten of the 14 SIM subjects and nine of the 12 control subjects achieved satisfactory test performance, learning a minimum of two modules. Of these, the SIM subjects had significantly better survey knowledge than Control subjects in terms of their ability to point to unseen landmarks. They were approximately twice as accurate and twice as fast than the Control group. SIM subjects performed especially well for targets in the forward direction and surpassed Control subjects in the tasks when their initial body roll angle was changed. Unexpectedly, the two groups did not differ significantly in their answers to most of the route description questions, which measured landmark and route knowledge, possibly because the SIM tool allowed the subjects to also utilize local visual cues. SIM subjects were significantly more likely to correctly answer a question that demonstrated understanding of relationships between modules' vertical upright. The results suggest that SIM is a promising tool for space station training. (Supported by Grant NAG9-1004 from NASA Johnson Space Center Space Human Factors Engineering program.)

NP1.9

Dynamic visual acuity during locomotion using far and near targets

Brian T. Peters[1,2], Jacob J. Bloomberg[3]
[1]Neuroscience Laboratories, Wyle Life Sciences, Houston, TX; [2]Department of Exercise Science, University of Massachusetts, Amherst, MA; [3]Neuroscience Laboratories, NASA/JSC, Houston, TX

Dynamic Visual Acuity (DVA) has previously been used to study vestibulo-ocular reflex (VOR) function (Demer et al., Am J Otol 15:340-347, 1994). In the case of a locomoting person, gaze control is a complex task requiring the contribution of several sensorimotor subsystems. As a result, degraded performance in one of the contributing subsystems (e.g. eye-head) can be accounted for by changes in another (e.g. head-trunk). Therefore, it may be the overall performance of the gaze control system during a natural activity that provides a relevant variable for assessing the recovery of a patient or an astronaut postflight. The purpose of this effort was to develop and test a tool for measuring the effectiveness of the gaze control system while walking and fixating targets at two viewing distances. DVA was used to determine the ability of subjects to stabilize gaze while standing quietly and while walking on a treadmill at 6.4 km/hr for both a NEAR (0.5m) and FAR (4.0m) target viewing distance. A computer program, modeled after the Freiburg Visual Acuity Test (Bach, Opt Vis Sci 73:49-53, 1996), was written to serially display Landolt-C optotypes with randomly generated orientations in sizes that correspond to acuities from 1.0 to –0.4 on the logMAR scale (Snellen fractions of 20/200 to 20/8). The optotypes were displayed on a laptop computer screen for the FAR condition while a microdisplay (Kopin Corporation, Taunton, MA) was required to attain the necessary screen resolution for the NEAR condition. For the pilot test results reported here, the optotype display duration was set to 500ms. Reported as deviations from the standing condition, the FAR and NEAR conditions showed changes of 0 ± 0.071 and 2.75 ± 0.050 (mean ± SD) on the logMAR scale, respectively. For reference, the +0.3 change experienced by 3 of the 4 subjects in the NEAR condition, is equivalent to a degradation in acuity from 20/20 to 20/40. These results correspond to subject reports of increased relative target motion during the NEAR condition. Using DVA as an evaluation tool may ultimately prove to be a simple method for assessing the performance of the gaze stabilization system. The Snellen fraction output of the computer program used here is an improvement over our previous attempts to collect DVA while walking. However, because visual fixation of a near target while walking is presumed to have a higher level of otolithic involvement, and it is the otoliths that are affected more by weightlessness, the more significant contribution of this effort for assessing astronaut performance postflight may be the ability to assess DVA during the NEAR condition.

NP1.10

Motion trajectory prediction cues alleviated simulator sickness during passive travel though a virtual environment

J.J.W. Lin[1], H. Abi-Rached[1], T.A. Furness[1], D.E. Parker[2]
[1]Human Interface Technology Laboratory, University of Washington, Seattle, WA; [2]Department of Otolaryngology, University of Washington, Seattle, WA

This study investigated cues that permit prediction of turns during passive movement through a virtual environment (VE). Effects on presence, enjoyment, and simulator sickness (SS) were examined. Previous research indicated that the ability to predict turns while driving reduced motion sickness. For passengers, prediction is based on seeing the road ahead of the car. Unexpected results from a preliminary study led to the following questions. Do cues that permit prediction of turns influence subjects' responses to presence / enjoyment / SS scales? Does awareness of cues influence subjects' responses? 12 subjects were exposed to complex motion through a cartoon-like simulated environment in a driving simulator. The simulator included a full-size car, 3 video projectors, and 3 230 x 175 cm screens. Each subject was exposed to each of 3 conditions for 2-min using a counterbalanced experimental design. Forward velocity was constant and the motion trajectory was the same across all conditions. In Condition 1, a green path through the simulation provided detailed cues for turns. In Condition 2 (simplified cues), the trajectory followed a green path that was drawn like a polygonal sidewalk. For Condition 3 (no turns cues), the green path was rotated 90˚ relative to the VE scene, but the trajectory was the same as in the previous conditions. Following each trial, subjects completed the Revised Simulator Sickness Questionnaire, a Presence / Enjoyment Questionnaire, and a Trajectory "Smoothness" scale. They were asked to report their awareness of the path after completing all conditions. SS in the no-cue condition were significantly higher than in the simplified-cue condition. Contrary to expectations, SS for the simplified-cue condition was slightly lower than for the detailed-cue condition. Subjects' responses on the presence and enjoyment scales were not different across the different levels of prediction cues. Although some reported noticing "different colors of grass" (the path was a darker green than the VE grass) none of the subjects reported distinguishable differences across Conditions 1-3. None reported recognizing that their motion through the VE followed a path. However, subjects reported, at a marginally significant level ($p = .052$), that the car motion was smoother for the detailed-cue than for the no-cue condition. Finally, there was a somewhat surprising and statistically significant difference in the mean ranks of the post-experiment, subjectively reported abilities to predict turns, which, from high to low, were Conditions 1, 2, and 3, respectively. Unobtrusive and unreported motion cues appeared to alleviate SS in a VE. This could be useful for VE training that requires trainees to attend to a task. The results from this study can be discussed in terms of the efferent copy / prediction models developed by von Holst, Mittelsteadt, Sperry and others. Unobtrusive motion trajectory cues for passive observers are among the interventions to alleviate SS in motion simulators and VEs being pursued at the Human Interface Technology Laboratory. (Supported by Eastman Kodak, Inc. and NASA Grant NCC 9-56.)

NP1.11

The role of visual inputs in adaptation to short-radius centrifugation

Erika L Brown
MIT Man-Vehicle Lab, Cambridge, MA

Artificial gravity provides a critical enabling technology for long-duration human missions both within and beyond Low Earth Orbit by providing an integrated countermeasure to microgravity deconditioning. Unfortunately, the constraints of current vehicles necessitate the use of high-velocity short radius centrifuges and rule out large rotating spacecraft. Head turns made at these high rates of rotation introduce a host of problematic vestibular responses, including disorientating illusions of self-motion, improper reflexive eye movements, and motion sickness. Young, et al (2001) provided evidence that, unlike previously thought, the vestibular side effects of 23-rpm short radius centrifugation can be overcome with proper adaptation. The problem that remains is one of optimization. We adapted 33 young adults to supine right-quadrant yaw head turns on-board a 2-m 23-rpm SRC. Data was collected both before and after a 10-minute adaptation period in one of three visual conditions: DARK, STABLE with a centrifuge-fixed visual field, and EXTERNAL with full view of the room. 1) Nearly all the parameters measuring subjective experience, including metrics of motion sickness and illusory self-motion, decreased significantly across days and phases. The visual condition encountered during adaptation played no significant role in this process. 2) There was a nearly significant effect of Day on the normalized slow phase eye velocity (NSPV) of (STABLE and EXTERNAL) subjects adapted with visual inputs. By contrast, no vestibulo-ocular reflex (VOR) adaptation was discernable for subjects adapted in the DARK. Visual inputs were required to adapt eye movements. 3) In subjects adapted with a view of the external world, the NSPV was significantly higher for turns to RED than to NU. This same trend was absent for groups adapted in the dark or with a stable visual field. 4) For all three experimental groups, head turns made to RED elicited less intense sensations of illusory motion than turns made to NU. This was in contrast to the differences described above for NSPV and points to dissociation between the adaptation of physiological parameters and subjective experience. Adaptation is a stimulus-specific process, designed to produce responses that are better attuned to a given situation. While the visual feedback of retinal slip was necessary to adapt inappropriate eye movements, all three groups adapted equally well in terms of their motion sickness scores and the intensity of their experienced illusory body tilt. Rotation in a STABLE visual surround offers a number of operational advantages in a flight situation, including provisions for reading or use of a head-mounted virtual display to provide entertainment, interactive exercise routines, or training scenarios during centrifugation. Therefore, we recommend this paradigm for use in countermeasure development.