RISK OF SENSORY-MOTOR PERFORMANCE FAILURES AFFECTING VEHICLE CONTROL DURING SPACE MISSIONS: A REVIEW OF THE EVIDENCE

William H. Paloski[1,2], Charles M. Oman[3], Jacob J. Bloomberg[1], Millard F. Reschke[1], Scott J. Wood[1], Deborah L. Harm[1], Brian T. Peters[1], Ajitkumar P. Mulavara[1], James P. Locke[1], and Leland S. Stone[4]

[1] *NASA Johnson Space Center, 2101 NASA Parkway, Houston, TX 77058 (USA)*
[2] *University of Houston, 3855 Holman St, Houston, TX 77204 (USA)*
[3] *Massachusetts Institute of Technology, 77 Massachusetts Ave., Cambridge, MA 02139 (USA)*
[4] *NASA Ames Research Center, Moffett Field, CA 94035(USA)*

Paloski, W.H., C.M. Oman, J.J. Bloomberg, M.F. Reschke, S.J. Wood, D.L. Harm, B.T. Peters, A.P. Mulavara, J.P. Locke, and L.S. Stone. Risk of sensory-motor performance failures affecting vehicle control during space missions: a review of the evidence. *J. Grav. Physiol. 15(2):1-29, 2008.* – NASA's Human Research Program (HRP) has identified a number of potentially significant biomedical risks that might limit the agency's plans for future space exploration, including missions back to the Moon and on to Mars. Among these risks is the: "*Risk of Impaired Ability to Maintain Control of Vehicles and Other Complex Systems.*" We examine the various dimensions of this risk by reviewing the research and operational evidence demonstrating sensory-motor performance decrements during space flight that might affect vehicle and complex system control, including decreased visual acuity, eye-hand coordination, spatial and geographic orientation perception, and cognitive function. Furthermore, we evaluate this evidence to identify the current knowledge gaps that must be filled through further research and/or data mining efforts before the risk can be fully mitigated. We conclude that the true operational risks associated with the impacts of adaptive sensory-motor changes on crew abilities to control vehicles and other complex systems will only be estimable after the gaps have been filled and we have been able to accurately assess integrated performance in off-nominal operational settings.

Key words: Vestibular, Visual, Spatial disorientation, Eye-hand coordination, Gravito-inertial force

INTRODUCTION

NASA's Human Research Program (HRP) has identified a number of potentially significant biomedical risks that might limit to the agency's plans for future space exploration, which include missions back to the Moon and on to Mars. Among them is the: "*Risk of Impaired Ability to Maintain Control of Vehicles and Other Complex Systems*," which is described as follows: "*Space flight alters sensory-motor function, as demonstrated by documented changes in balance, locomotion, gaze control, dynamic visual acuity, eye-hand coordination, and perception. These alterations in sensory-motor function affect fundamental skills required for piloting and landing airplanes and space vehicles, driving automobiles and rovers, and operating remote manipulators and other complex systems. However, relationships between the physiological changes and real-time operational performance decrements have not yet been established, owing to both the inaccessibility of operational performance data and the presence of confounding, non-physiological factors in most known instances of significant operational performance decrement. While space flight induced alterations in sensory-motor performance are of concern for upcoming lunar missions, they are of greater concern for Mars missions due to the prolonged microgravity exposure during transit, which will more profoundly affect landing task performance and subsequent operation of complex surface systems.*"

Address for correspondence:
William H. Paloski, Ph.D.
Department of Health and Human Performance
3855 Holman St. Garrison Room 104
Houston, TX, 77204-6015
Email: whpaloski@uh.edu

Control of vehicles and other complex systems is a high-level integrative function of the central nervous system (CNS). It requires well-functioning subsystem performance, including good visual acuity, eye-hand coordination, spatial and geographic orientation perception, and cognitive function. Evidence from space flight research demonstrates that the function of each of these subsystems is altered by removing gravity, a fundamental orientation reference, which is sensed by vestibular, proprioceptive, and haptic receptors and used by the CNS for spatial orientation, navigation, and coordination of movements. The available evidence also shows that the degree of alteration of each subsystem depends on a number of crew- and mission-related factors.

There is only limited operational evidence that these alterations cause functional impacts on mission-critical vehicle (or complex system) control capabilities. Furthermore, while much of the operational performance data collected during space flight has not been available for independent analysis, those that have been reviewed are somewhat equivocal owing to uncontrolled (and/or unmeasured) environmental and/or engineering factors. Whether this can be improved by further analysis of previously inaccessible operational data or by development of new operational research protocols remains to be seen. The true operational risks will be estimable only after we have filled the knowledge gaps and when we can accurately assess integrated performance in off-nominal operational settings.

Thus, our current understanding of the *Risk of Impaired Ability to Maintain Control of Vehicles and Other Complex Systems* is limited primarily to extrapolation of scientific research findings, and, since there are no robust ground-based analogs of the sensory-motor changes associated with space flight, observation of their functional impacts is limited to studies performed in the space flight environment. Fortunately, many sensory-motor experiments have been performed during and/or after space flight missions since 1959 (150). While not all of these experiments were directly relevant to the question of vehicle/complex system control, most provide insight into changes in aspects of sensory-motor control that might bear on the physiological subsystems underlying this high-level integrated function.

I. EVIDENCE

A. Space Flight Evidence

To our knowledge, no relevant, randomized, controlled, human flight research investigations have been performed. Thus, this section begins with a summary of evidence obtained form observations of crew performance decrements during operational situations. While largely circumstantial and clearly multi-factorial (likely resulting from a combination of physiological, behavioral, environmental, and engineering factors), this evidence provides a basis for concerns regarding the operational impacts of sensory-motor adaptation to space flight, as well as justification for continued investigation into the relative roles of the various factors affecting crew performance. Following the operational evidence section, summaries of evidence are provided in separate sections for each of four physiological sub-issues related to the subject risk (oculomotor control, eye-hand coordination, spatial disorientation, and cognition). Within each section, the levels of evidence should be clear from context and/or references. Where necessary supporting studies from space flight analog environments (e.g., parabolic flight), space flight analog populations (e.g., vestibular deficient patients), or other critically relevant ground-based investigations are included.

1. Evidence Obtained from Space Flight Operations

An accurate assessment of the risks posed by the impacts of physiological and psychological adaptations to space flight on control of vehicles and other complex systems must account for the potentially off-setting influences of training/recency and engineering aids to task performance. Thus, it behooves us to review performance data obtained from space flight crews engaged in true mission operations. Evidence of operational performance decrements during space flight missions has been obtained from several sources; however, to our knowledge no well-designed scientific studies have been performed on critical operational task performance, so interpretation is frequently confounded by small numbers of observations, inconsistent data collection techniques, and/or uncontrolled engineering and environmental factors. Much of the relevant, extant operational data has been previously inaccessible to (or uninterpretable by) life sciences researchers. Recent programmatic changes have putatively improved access to both data and experts to help with interpretation, though, so a major near-term goal is to mine these operational data to better assess what we already know about the risk.

Crew Verbal Reports A number of (unpublished) crew verbal reports were obtained early after flight by some of the authors of this paper. While difficult to combine, owing at least in part to the lack of standardized questions and structured interview techniques, these reports are informative in that they provide insight into the individual crewmember perceptions. As an example, the following transcript (obtained by Dr. Reschke) captures impressions from a Shuttle commander obtained immediately (<4 hrs) after flight. The discussion focused on target acquisition tasks the commander performed for Dr. Reschke during the flight and his difficulties with nausea, disorientation, posture, locomotion, etc. after the flight (*italicized text* indicates the crewmember's responses to the Dr. Reschke's questions).

Did you try to limit your head movements? *Oh yes, definitely.* When you were trying to acquire the targets only, ...did you notice any difficulty in spotting the targets? *Oh yeah, oh yeah.* Did it seem as though the target was moving or was it you? *I felt that it was me. I just couldn't get my head to stop when I wanted it to.* So it was a head control problem? *Yeah, yeah in addition to the discomfort problem it caused.* So when you first got out of your seat today, can you describe what that felt like? *Oh gosh, I felt so heavy, and, uh, if I even got slightly off axis, you know leaned to the right or to the left like this, I felt like everything was starting to tumble.* When you came down the stairs did you feel unstable? *Oh yeah, I had somebody hold onto my arm.* Did you feel like your legs had muscle weakness, or … was it mainly in your head? *It was mainly in my head.*

Every crewmember interviewed by one of us on landing day (>200 crewmembers to date) has reported some degree of disorientation/perceptual illusion, often accompanied by nausea (or other symptoms of motion sickness), and frequently accompanied by malcoordination, particularly during locomotion. Of particular relevance to the ability to perform landing tasks, common tilt-translation illusions (see below) include an overestimation of tilt magnitude or misperception of the type of motion. Most also reported having experienced similar symptoms early in flight; however, except in the most severely affected, there seems to be no correlation between the severity of the symptoms following ascent and those following descent. The severity and persistence of postflight symptoms varies widely among crewmembers, but both tend to decrease with increasing numbers of space flight missions. However, both severity and persistence increase with mission duration. Symptoms generally subsided within hours to days following 1-2 week Shuttle missions but persisted for a week or more following 3-6 month Mir Station and ISS missions. The degree to which these psychophysical effects might affect piloting skills is difficult to judge, as recent, intensive training may have offset any impact on Shuttle landings, especially under nominal engineering and environmental conditions, and long duration Mir and ISS crewmembers to date have only piloted ballistic entry spacecraft, which parachute in, allowing no human control inputs during the last 15 min before landing.

<u>Shuttle Entry and Landing Spatial Disorientation</u>

Despite recent, intensive training for all Shuttle commanders and pilots, some Shuttle landings were outside of the desired performance specifications, perhaps, in part, because of spatial disorientation. Shuttle entry and landing spatial disorientation (SD) differs from aviation SD (see below), at least in terms of prevalence. Most instrument rated aircraft pilots have experienced SD, but episodes occur relatively infrequently in ordinary flying. In contrast, stimuli capable of producing SD are present during every Shuttle landing. At issue is whether the astronaut commander can successfully fly through the SD. Tilt-translation illusions (see below) do not occur in astronauts practicing approaches in the Shuttle Training Aircraft (STA), so their first actual experiences with these illusions occur during their first actual return from space. Crews are forewarned about them, but so far we do not know how to predict the direction and magnitude of the effect, so a first-time flier cannot know in advance which way to compensate. This is generally handled operationally by requiring commanders to have previous space flight experience (as pilots). Fortunately, on the 120+ Shuttle flights to date, there have been no accidents specifically attributed to SD. However, several lines of circumstantial evidence suggest that the margin for error may be less than generally recognized.

Shuttle landings, to date, have all been successful, but landing performance has been more variable than desired. The timing and shape of the commander's control input during the flare depends critically on correct perception of speed, altitude, attitude, and sink rate. The flare maneuver, in turn, determines the readily measurable landing performance metrics, such as touchdown sink rate, speed, and distance. Of all the landings between STS-1 and STS-108, the Shuttle crossed the runway threshold abnormally low 20 times. Seven landings touched down abnormally long or short, and 13 had high touchdown sink rates, with three exceeding the 5 ft/sec structural limit. Moore *et al.* (118) recently reported that touchdown speeds during the first 100 Shuttle landings varied widely, with 20% outside of acceptable limits and six equaling or exceeding the maximum speed of 217 knots/hr (main landing gear tires are rated at 225 knots/hr maximum speed). They also note that the fastest landing on record (224 knots/hr) was linked to the commander's momentary spatial disorientation (32), as was the second fastest (220 knots/hr). Normally, commanders perform better than this when flying the STA and the flight simulators. A different analysis of Shuttle landing compared piloting performances in terms of sink rate at touchdown. Fig. 1 shows preflight performances flying the STA and subsequent postflight performances in the Shuttle by commanders of all missions from STS-43 to STS-108. The average STA and STS touchdown sink rates were similar, and almost all STA touchdown sink rates fell in the desirable range; however, the STS touchdown

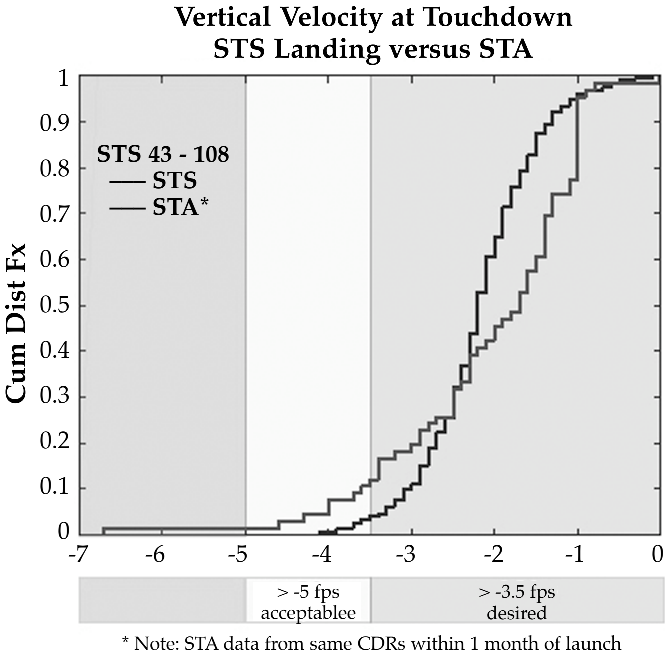

Figure 1. Cumulative distribution functions allowing comparison between landing performances (vertical velocity at touchdown) before flight in the Shuttle Training Aircraft (STA) and those at the end of mission in the Space Shuttle (STS).

sink rate distribution exhibits greater variability, with more than 10% exceeding the desired sink rate at touchdown.

Of particular note was the landing of the eight-day STS-3 mission in 1982. The commander, who was flying visually, took over manual control of the vehicle 30 seconds before landing at White Sands, NM. The vehicle was decelerating at 0.25 g. Starting at flare, when the commander attempted to lower the nose of the Shuttle, the vehicle exhibited a pilot induced oscillation (PIO) of three full cycles with increasing amplitude that continued through touchdown. Post-flight analysis showed no engineering anomaly in the flight control system. The commander was a highly experienced test pilot, very familiar with conventional PIO and with the 0.25g deceleration of landing. However, it is possible that he underperceived his pitch attitude because of tilt-translation ambiguities and caused the PIO by making larger control stick movements than necessary to compensate for the misperception. This could have been further exacerbated by inappropriate manual control inputs to the stick caused by miscalibration of eye-hand coordination. In a recent interview, however, the commander denied having any issue with PIO, or misinterpreting pitch attitude. His recollection was that the nose came down earlier than expected as the Shuttle began to slow down. He said the stick was not responsive when he first attempted to pitch the nose back up, but then it seemed to over-respond and pitched up more than he expected. Because he was then concerned about a potential problem with the stick, he brought the nose down and left it down. The commander's recollection appears to be consistent with the landing video, but not with data from the control stick that showed five large amplitude reversals in the pitch plane command after main gear touchdown. While difficult to reconstruct so long after the event, this may be noteworthy as an unrecognized case of spatial disorientation in a highly experienced pilot.

Increasing pilot awareness of the PIO problem, modifying software to reduce control authority automatically when oscillatory control outputs are detected, adding a heads-up display (HUD) pitch attitude read-out, and restricting landings to low cross-wind and good visibility conditions have so far prevented PIO recurrence. However, it is clear that control phase and gain margins during the landing maneuver are routinely near limits of stability, and that pilots making their first Shuttle landing must overcome disorienting perceptions not encountered during preflight training in the STA.

Flight surgeons now examine every returning Shuttle crewmember for evidence of neurological dysfunction within several hours of landing. Crewmembers are scored for subjective symptoms, coordination, and functional motor performance. McCluskey *et al.* (102) analyzed data from nine missions, and noted trends, such as a correlation between touchdown sink rate and postflight difficulty performing a sit-to-stand maneuver without using the arms. Scores indicating neuro-vestibular dysfunction generally correlated with poorer flying performances, including a lower approach and landing shorter, faster, and harder.

These observations suggest that further analysis of Shuttle landing performance is required. Where possible, objective landing performance data should be compared directly with objective sensory-motor physiological data to determine what associations exist between landing performance and physiological adaptation.

Apollo Lunar Landing Spatial Disorientation The Apollo Lunar Module (LM) had a digital autopilot that on later missions was capable of fully automatic landings. While the Apollo crews used the autopilot through most of the descent, all elected to fly the landing phase manually, using angular rate and linear velocity control sticks to adjust the vehicle trajectory while visually selecting the landing point. Landing sites and times were chosen so that the sun angle provided good visibility, but the crews had problems recognizing landmarks and estimating distances because of ambiguities in the size of terrain features. The vehicles had no electronic map or landing profile displays. The commander flew visually, designating the landing spot using a window reticle, while the second astronaut verbally annunciated vehicle states and status. Unfortunately, the landing area was generally not visible to the crew until the LM pitched to nearly upright at an altitude of about 7000 feet and distance of about 5 miles from touchdown with only 1-2 minutes of fuel remaining. Spatial disorientation was a concern during landing because visibility was reduced by the window design (views downward and to the right were blocked) and by lunar dust blowback that impaired surface and attitude visibility. For example, the Apollo 11 and 12 crews reported difficulty in nulling horizontal rates during landing because of blowing dust, and the Apollo 12 and 15 crews reported virtually no outside visibility in the final moments of landing. Visibility was improved in later missions by new hovering maneuvering procedures that reduced blowing dust.

Horizontal linear accelerations could not be avoided during the gradual descent to the landing zone or during hover maneuvers just before touchdown. Since lunar gravity is only 1/6 that on Earth, lunar landers had to pitch or roll through angles six times larger than on Earth to achieve a given horizontal acceleration using the engine thrust vector. The directional changes in gravito-inertial force these tilts created would have been larger than those on Earth, arguably making tilt-translation ambiguity illusions more likely. The Apollo crews trained for their missions in a 1/6 g Lunar Landing Training Vehicle, which did not simulate the vestibular effects of 1/6 g. Prior to their missions the only 1/6 g vestibular stimulation they received was during limited parabolic flight training. With the world watching, the Apollo crews did not acknowledge any spatial disorientation events during landing. They did later admit feeling a little "wobbly" when they emerged to walk onto the lunar surface, but reported that coordination improved steadily during first few hours of lunar ambulation.

Apollo Landing Geographic Disorientation The Apollo LM utilized inertial navigation, updated by occasional star sights, radar orbital data from Earth, and radar altimetry during descent. Nonetheless, there was uncertainty in the accuracy of their computed position as they descended into the landing zone. Since crews could not look straight down, the final approach trajectory to the landing area had to use low angles (16-25°) so crew could see ahead. Mission planners only knew the landing zone terrain to 10 m resolution, so the crews had to confirm visually the LM trajectory and then sight the computer's anticipated touchdown point using a front window reticle. Given the fractal nature of lunar craters, identification of surface features was challenging. Humans interpret surface shape from shading based on a "light comes from above" assumption. This can create a "Moon crater" illusion (146) in which distant concave features, such as lunar craters, can be perceived as convex objects, such as hills, when viewed looking "down sun." The crews had to choose a suitably flat landing area, as judged by surface albedo and the absence of shadows indicating small craters or fissures. Landings were planned with sun elevations of 5-23°, so shadows were of moderate length, and with the crew facing down sun at a slight angle, so that shadows would be visible. The human eye can resolve 1.5 ft detail at a distance of about 4000 ft. As more surface details became visible, the commander typically redesignated the landing point (often several times), and eventually took over and flew manually, usually to a point somewhat beyond the final computer redesignated spot. He judged horizontal velocity looking out the window or using a cockpit Doppler radar display, and he used the LM shadow as a gauge, while listening to callouts of altitude, altitude rate, horizontal velocities, and fuel status. Since surface slope is impossible to judge visually looking straight down, the commander chose the final landing spot looking horizontally, and then flew over it and began final descent. At 50-100 feet, dust often obscured the outside view, and the vertical descent to touchdown sometimes had to be made relying primarily on instruments. The descent engine was cut off just before touchdown, to avoid explosion or damage should it contact the surface. The landing gear design assumed a maximum surface elevation difference of two feet within the landing gear footprint, and a maximum 12° terrain slope (157). Finding a flat landing spot was highly desirable, since vehicle tilts on the surface complicated surface operations and subsequent takeoff.

All six Apollo landings were ultimately successful. However, the Apollo 15 crew experienced geographic disorientation. When they pitched over, they could not identify the craters they were expecting, and the commander had to choose a landing spot in an unplanned area. Maintaining full awareness of the terrain immediately beneath the lander was usually impossible during the final phase of landing, and in one case the LM engine was damaged on touchdown (82, 113). The Apollo 12 commander encountered heavy dust blowback and said, *"I couldn't tell what was underneath me. I knew it was a generally good area and I was just going to have to bite the bullet and land,* *because I couldn't tell whether there was a crater down there or not.*" He later added, "*It turned out there were more craters there than we realized, either because we didn't look before the dust started or because the dust obscured them.*" The following mission, Apollo 14, landed safely, but on a seven-degree slope. Apollo 15 experienced severe dust blowback that contributed to making the hardest landing of the program (6.8 ft/sec), with the vehicle straddling the rim of a 5 ft deep crater, buckling the bell of the descent engine, and causing an 8°vehicle tilt. Apollo 16 and 17 experienced less dust obscuration and landed closer to level.

It seems likely that similar problems will be encountered when crews once again begin landing vehicles on the lunar surface. Improved navigation aids could help to avoid geographic disorientation, and increased reliance on auto-land capabilities could help maintain the landing performance within equipment specifications. However, improved training techniques, including realistic simulation of visual-vestibular inputs, will likely be required should commanders choose to use manual landing modes. The challenge of manual landing is likely to be much greater for Mars landings, owing primarily to the increased transit time in microgravity. A combination of more profound adaptation to microgravity and decreased training recency will likely increase substantially the risks associated with manual landing on Mars. [Note that using continuous artificial gravity, created by rotating all or part of the vehicle during transit, might well mitigate this risk (as well as many of the other biomedical risks), but the impact of prolonged exposure to a rotating environment on piloting a spacecraft would need to be investigated before committing to such a solution.]

<u>Rendezvous and Docking</u> A top priority in the U.S. space program is assuring crew and vehicle safety. This priority gained significant focus in June 1997 following the collision of the Progress 234 resupply ship with the Mir space station during a manual docking practice session. There were two separate attempts to dock the Progress with the Mir that day. In the first attempt, docking was aborted after the radar used for range calculations apparently interfered with a camera view of the Progress. In the second, near fatal attempt, mission managers decided to turn the radar off and leave the camera on. For this arrangement to work the Mir commander asked his two crewmates to look for the Progress approach through a porthole, and once sighted, to provide range information with handheld range instruments. Trouble began when neither the camera view nor the visual spotters could locate the Progress as it closed on the station. When spotters moved between modules to obtain a better view, they lost their frame of reference, and were uncertain which direction to look. Once spotted, the Progress' speed was above an acceptable rate, and it was very close to the Mir. Braking rockets on the Progress, fired by the Mir commander, failed to slow the velocity of the approaching spacecraft. No range information or other position data were available to assist the commander. To complicate matters, one of the other crewmembers may have bumped into the commander as he attempted to make last second inputs to the approaching Progress via joystick. The resulting collision tore a portion of the solar panel on the Mir, punched a hole in the Spektr module, and caused a decompression of the station.

Loss of situational awareness, spatial disorientation, and sensory-motor problems, including difficulties with vision, head-hand-eye coordination, and an inability to judge distance and velocity with limited feedback likely contributed to this outcome. Target acquisition studies have shown dramatic changes in the speed at which target visualization can be achieved, delaying response time by as much as a 1000 msec. Eye-hand response could take as long as another full second. A delay of two seconds is a lifetime when a spacecraft is closing, and not responding to joystick commands intended to decrease forward velocity. Members of the Russian Institute of Biomedical Problems (IBMP) believe that the collision between Mir and Progress was caused by poor situational awareness, spatial disorientation, and sensory-motor problems (I.B. Kozlovskaya, personal communication). After the fact, Ellis (48) performed a rigorous, quantitative analysis of the available visual and non-visual information and suggested a number of potential sensory-motor and cognitive/psychophysical contributions to the crash. To avoid human factors contributions to future crashes such rigorous analyses should be performed well before attempting any three-dimensional visual-motor control task.

<u>Teleoperator Tasks</u> The ISS teleoperation system has been heavily used in ISS construction, and it will continue to be used to support EVA operations, as well as in grappling/docking of rendezvousing cargo vehicles. Training and operating the Shuttle and ISS telerobotic manipulator systems as well as telerobotically controlled surface rovers presents significant sensory-motor challenges (40, 91, 106). These systems are usually controlled using separate rotational and translational hand controllers, requiring bimanual coordination skills and the ability to plan trajectories and control the arm in some combination of end-effector or world reference frames. The abilities to

visualize and anticipate the three-dimensional position, motion, clearance, and mechanical singularities of the arm and moving base are critical. Thus, operators must have the cognitive abilities to integrate visual spatial information from several different reference frames. Often the video cameras are not ideally placed, and in some situations (e.g. ISS operations) the views may actually be inverted with respect to one another, so cognitive mental rotation and perspective taking skills are also important (91, 106). Teleoperation is sufficiently difficult that several hundred hours of training are required to qualify, and all operations are monitored by a second qualified operator, backed up by a team of trainers and engineers on the ground. Recency is important, so ISS astronauts perform on-orbit refresher training. Despite all the training and precautions, however, there have been four-five significant ISS teleoperation incidents (e.g., collisions with a payload bay door, significant violations, or close calls) over the course of the first 16 ISS increments (185). Procedures are updated after each incident, but there are generic common factors relating to spatial visualization skills, misperception of camera views, timeline pressures, and fatigue.

Driving Performance Driving a vehicle is one of the most complex sensory-motor/cognitive tasks attempted by most humans, and driving performance is known to be impaired in vestibular patients (38). Page & Gresty (131) reported that vestibular patients experience difficulty in driving cars, primarily on open, featureless roads or when cresting hills, and MacDougal & Moore (97) reported that the vertical vestibulo-ocular reflex contributes significantly to maintaining dynamic visual acuity while driving. Adaptive changes in sensory-motor function during space flight can compromise a crewmember's ability to optimize multi-sensory integration, leading to perceptual illusions that further compromise the ability to drive under challenging conditions. During the June 2006 Apollo Medical Operations Summit in Houston, TX, Apollo crewmembers reported that rover operations posed the greatest risk for injury among lunar surface EVA activities. During rover operations, crewmembers often misperceived the angles of sloped terrain, and the bouncing from craters at times caused a feeling of nearly overturning while traveling cross-slope, causing the crewmembers to reduce their rover speed as a result (Apollo 15 report). This is not surprising given the evidence of tilt-translation disturbances following G-transitions, as incorrect perceptions of vehicle accelerations, tilted terrain, and uneven (bumpy) surfaces may cause inappropriate responsive actions. While automatic control systems can compensate for some deficiencies in performance, lessons learned from the Apollo missions (113) suggest that manual takeover is required as a minimum safe guard, and therefore countermeasures must concentrate on mitigating risks associated with crewmembers in the control loop for rover operations.

Implications for CEV Design There are specific spatial disorientation issues to address with the crew exploration vehicle (CEV) currently being designed for lunar missions. As a capsule, CEV will differ from the Shuttle in opportunities to induce disorientation. In the CEV, crews will stow their seats after ascent, so there will be no up/down cues except for the cockpit panels and the windows. CEV, like Shuttle, will probably be manually docked when crewed, while the logistics (cargo) version may have auto-docking. The crew's ability to remain visually oriented with ISS during proximity operations is a concern (S. Robinson, CEV Cockpit Team, personal communication). The developers must undertake analyses to ensure that the integrated visual out-the-window, camera imagery, display information, and sensor data will be sufficient to perform the envisioned three-dimensional docking tasks reliably.

2. EVIDENCE OBTAINED FROM SPACE FLIGHT SCIENTIFIC INVESTIGATIONS

Studies Demonstrating Decrements in Visual Performance

High visual acuity is critical to performing piloting tasks, and it is very important to controlling other vehicles (e.g., rovers and automobiles) and complex systems (e.g., robotic arms and other remote manipulators). Rapidly locating and reading instrument displays, identifying suitable landing locations, free of craters, rocks, etc., and tracking the motion of targets and/or objects being manipulated are among the tasks requiring good vision enabled by optimized eye movement control. A large body of evidence demonstrates that the G-transitions associated with space flight disrupt oculomotor performance. Highlights are summarized in the following subsections.

Static Visual Acuity Space flight studies of static visual acuity, contrast sensitivity, phoria (relative directions of the eyes during binocular fixation), eye dominance, flicker fusion frequency, and stereopsis (ability to perceive depth) have been performed to determine whether space flight causes inherent changes in ocular function that affect visual performance (reviewed in Clément (37)). Except for contrast sensitivity, in-flight studies have revealed minimal

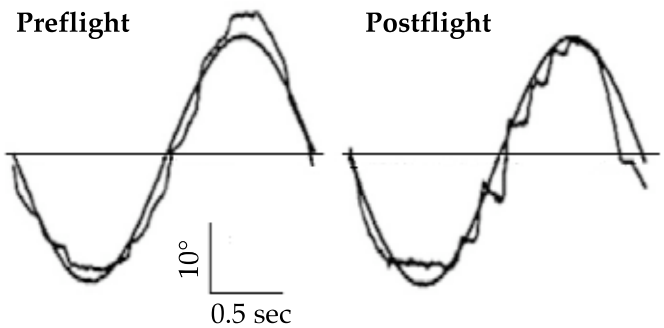

Figure 2. Smooth pursuit eye movements in the vertical plane before and after space flight (154). The smooth sinusoidal line represents the target motion, while the other line represents the eye movements. Note the presence of saccades after flight but not before flight.

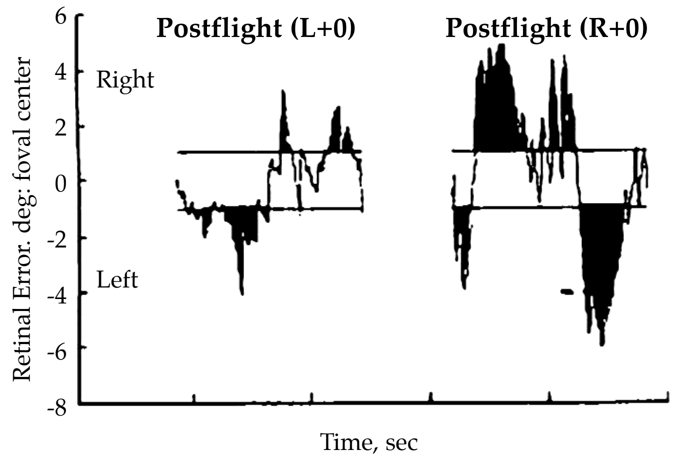

Figure 3. Cumulative time foveation is off target during the smooth pursuit-tracking task depicted in Figure 2.

changes in visual function (55, 168). However, in subjective clinical reports from 122 Shuttle crewmembers between 1995 and 1998, 15% indicated decrements in near vision acuity during flight (Longitudinal Study of Astronaut Health). This decreased acuity likely results from fluid shifts or gravity-related changes in ocular geometry (37), and it is generally overcome by using magnifying spectacles and/or large font sizes on documents and displays.

Smooth Pursuit Eye Movements To see an object clearly, the visual axis of the eye must be aligned to project the object of interest onto the fovea, a small region, centrally located on the retina, containing high concentrations of rods and cones. To accomplish this during voluntary visual tracking of moving targets (e.g., a bird flying by) without head movements, the CNS oculomotor control system produces smooth pursuit eye movements. Reschke *et al.* (149, 154) reported that space flight disrupts smooth pursuit eye movements (Fig. 2). Testing 39 crewmembers from 20 separate Shuttle flights using a simple point stimulus sinusoidal tracking task (0.33 Hz in either horizontal or vertical planes), they found that, relative to preflight values, eye movement amplitudes were reduced and the number of corrective saccades was increased just after flight. The functional impact is that visual acuity would be degraded by this inability of the oculomotor control system to keep target of interest focused on the fovea (Fig. 3). In other studies, André-Deshays *et al.* (1) found no in-flight changes in horizontal or vertical smooth pursuit tracking performance two Mir Station cosmonauts, but, Kornilova *et al.* (87) found changes similar to those reported by Reschke *et al.* (149) during other Mir station flights. Early in-flight they found that the eye movement amplitude responses to vertical pulsed movements of a point stimulus decreased (undershot the target) and numbers of corrective saccades increased relative to preflight values. They also reported performance deterioration in pursuit tracking of a point stimulus moving vertically or diagonally, with these effects being most pronounced early in-flight (flight day 3), late in flight (flight days 50, 116, and 164), and early after flight. Thus, it appears that during and early after space flight the amplitude of smooth pursuit eye movements is reduced, the saccadic system must be utilized extensively to maintain accurate target tracking, and vision is degraded by an inability to maintain the target focused on the fovea.

Vestibulo-Ocular Reflex (VOR) Function During head and/or body movements, the gaze stabilization system maintains high visual acuity by coordinating movement of the eyes and head so as to stabilize the image of interest on the fovea. The vestibulo-ocular reflex (VOR), a servo system that uses head motion signals sensed by the semicircular canals and otolith organs to generate vision-stabilizing compensatory eye movements, is critical to this function. Blurred vision, oscillopsia (illusory movement of the visual world), and/or reduced dynamic visual acuity occur when this gaze compensation mechanism is disrupted. Vestibulo-ocular reflex function is plastic, meaning it can adapt to different environmental stimuli (16). For example, the VOR gain (amount of eye rotation caused by a unit of head rotation) adapts when individuals begin wearing new prescription eyeglasses. A number of relevant flight experiments have demonstrated that various VOR response properties are modified during and after space flight, and that the degree of adaptation varies among subjects and experimental conditions (reviewed Reschke *et al.* (154)). Some of these are summarized in the following

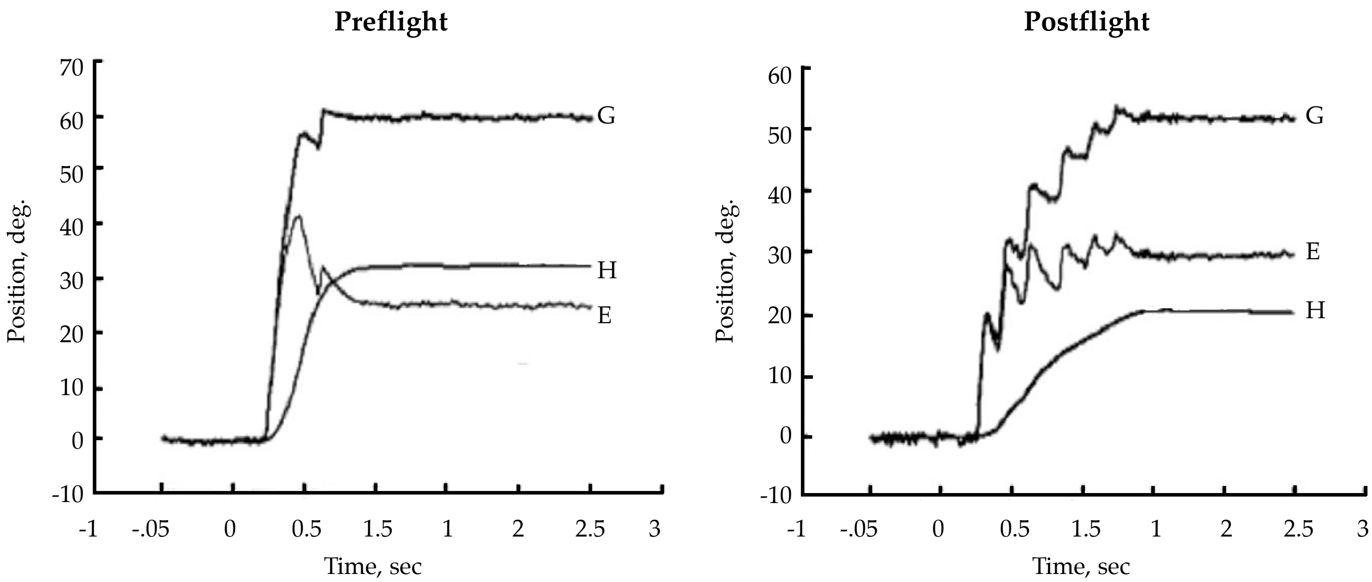

Figure 4. Head (H), eye (E), and gaze (G) movements during target acquisition beyond the effective oculomotor range before (left panel) and after (right panel) flight.

paragraphs.

Several investigations were conducted to determine the effects of weightlessness on the VOR responses to horizontal angular (yaw) head motions. Early studies relied mainly on voluntary (active) head oscillations to stimulate the VOR at frequencies ranging from 0.25 to 1 Hz (13, 170, 173, 176, 180), but passive rotational stimulation was sometimes employed before and after flight (13). These early studies detected no significant in-flight or postflight changes in yaw VOR gain, or, when changes were observed (60), the direction of the changes varied among subjects. Later experiments associated with the D-1, SLS-1, and SLS-2 Spacelab missions utilized passive body movements provided by step changes in the angular velocity of rotating chairs to stimulate the VOR. During parabolic flight, the persistence of the yaw VOR response after the chair motion stopped was decreased in eight astronauts tested just before space flight (124, 130) and in normal subjects (44). However, after 4-10 days in orbital flight, the yaw VOR persistence was no different from preflight values in five of the eight astronauts tested, although active head pitch movements ("dumping") did not interfere with the VOR persistence, as it consistently did on Earth. Early after flight (1-2 days), the persistence was decreased relative to preflight in nine of 12 astronauts tested, but it eventually returned to preflight values in all (124, 126, 130). These findings suggest that transitions to and from weightlessness temporarily reduce the contribution of brainstem mechanisms that normally extend the low frequency bandwidth of the human angular VOR response.

Unlike yaw plane head movements, pitch and roll plane head movements in normal gravity change the orientation of the head relative to the gravity vector, thereby modulating gravitational stimulation of the otolith organs. One might expect, therefore, that the pitch and roll plane VOR would be more affected by space flight than the yaw plane VOR. The pitch VOR response to voluntary head oscillations has been measured during and after space flight at frequencies comparable to those described above for yaw. While Watt *et al.* (180) reported no changes in pitch VOR during or after flight, others have reported changes. For example, Berthoz *et al.* (15) found that the VOR gain in subjects exposed to 1 Hz pitch head oscillations was significantly increased 14 hrs after landing when compared with late in-flight (flight day 5 and 7) and subsequent postflight measurements. They also reported an increased phase lag (delay between head motion and elicited eye motion) during the in-flight tests. However, the change in gain and phase relationship was not significant due to a high dispersion of the data. In a separate study, Viéville *et al.* (176) reported a decrease in vertical VOR gain for 0.25 Hz voluntary pitch oscillations in a subject tested on STS-51G. In another series of experiments examining cosmonauts returning from space flight, Clarke *et al.* (34, 35) reported decreased vertical VOR gains for head oscillations ranging from 0.12 Hz to 2.0 Hz, and a reversal of the normal asymmetry of vertical VOR gain, with greater gains during downward head movements than during upward movements. They also reported changes in torsional VOR during voluntary head movements in the roll plane during and after space flight. These findings further demonstrate that VOR is disrupted early after insertion into orbit and again following the return to Earth. Fortunately, central adaptive processes re-establish VOR response properties over time in the new environment, resulting in recovery of accurate stabilization of vision during head and/or body movements in the new environment. However, critical mission activities requiring accurate gaze stabilization during head movements (e.g., piloting/landing a spacecraft) will likely be performed less skillfully during or soon after G-transitions.

Eye-Head Coordination and Target Acquisition Gaze is the direction of the visual axis in three-dimensional space. It is defined as the sum of eye position with respect to the head and head position with respect to space. Acquisition of new visual targets of interest is generally accomplished using coordinated eye-head movements consisting of a saccadic eye movement that shifts gaze onto the target combined with a VOR response that maintains the target on the fovea as the head moves to its final position. Space flight modifies eye-head coordination during target acquisition (88, 171) and ocular saccadic performance (1, 149, 154, 175). Reschke *et al.* (149) also showed that performance of target acquisition tasks requiring coordinated eye-head movements is degraded during and after space flight, particularly for targets placed outside the central field-of-view in the vertical plane, requiring pitch head movements for target acquisition (Fig. 4). Grigoryan *et al.* (61) showed that changes in these parameters after flight contributed to a near doubling of the latency required to fixate peripheral targets. Also, Sirota *et al.* (166) showed that during adaptation to space, non-human primates trained to perform a visual target acquisition task requiring accurate perception of peripheral targets showed delays in the onset of the gaze response and made significantly more errors in identifying the visual characteristics of the peripheral targets.

Dynamic Visual Acuity Oculomotor (gaze) control orchestrated by the CNS is critical to dynamic visual acuity, the ability to see an object clearly when the object, the observer, or both are moving. Deficient gaze control experienced following G-transitions cause oscillopsia, or blurred vision, and decrements in dynamic visual acuity, with stationary objects appearing to bounce up and down or move back and forth during head movements. Decreased dynamic visual acuity caused by space flight can lead to misperception of sensory information and poses a unique set of problems for crewmembers, especially during entry, approach, and landing on planetary surfaces. Visual disturbances could adversely affect entry and landing task performance, such as reading instruments, locating switches on a control panel, or evacuating a vehicle in suboptimal visual conditions (e.g., smoke in the cabin). Postflight oscillopsia and decreased dynamic visual acuity could decrease crewmember safety when returning to normal duties (*e.g.*, driving a rover, scuba diving, or piloting an aircraft) or activities of daily living (*e.g.*, driving, contact sports, climbing ladders, *etc.*) after flight.

Under certain conditions, even persons with healthy vestibular function can experience compromised visual performance. Human factors (*i.e.* ergonomics) investigations looking at the effects of whole-body vibration have documented changes in visual performance over a wide range of stimulus conditions (26, 59, 105, 119). An important factor for determining the visual performance in these investigations is the transmissibility of the vibration to the head. Factors such as the subject's posture and muscle tone, as well as their coupling to contact surfaces or added masses, can have an effect on visual performance. The coupling between astronauts and their spacecraft during critical phases of the mission (*e.g.*, entry, landing) could therefore affect their ability to see clearly. McDonald *et al.* (103) discussed the implications to gaze control of adaptive changes in musculoskeletal impedance and posture after space flight. Musculo-skeletal impedance is also affected by G-loading, which in turn affects vibration sensitivity; G- and vibration loading often occur together during launch and entry/landing. Visual performance may well be degraded while standing during piloting, as proposed for the currently planned lunar missions and previously employed during the Apollo program. In a series of experiments on returning crewmembers, Bloomberg and colleagues have documented decrements in dynamic visual acuity (DVA) while walking immediately after space flight. First, in a ground-based study, they demonstrated that DVA (assessed by having subjects read numbers of different font size while walking on a treadmill) was effective at identifying differences in visual performance between labyrinthine deficient patients (patients with vestibular system abnormalities) and a group of normative control subjects (72). The same paradigm was then used to demonstrate decreased DVA performance in astronaut subjects following return from long-duration space flight (17). More recently, a second-generation test (using Landolt C characters instead of numbers) was used to document decrements in DVA performance as a function of time after flight in 14 crewmembers returning from long-duration space missions (139). Acuity assessments were made both while standing still and while walking at

6.4 km/h on a motorized treadmill to produce body self-motion. The difference between the walking and standing acuity measures provided a metric of the change in the subject's ability to maintain gaze fixation on the visual target while walking. Postflight (one day after landing) changes in gaze control produced decreases in dynamic visual acuity during walking. For some subjects the decrement was greater than the mean acuity decrement seen in a population of vestibular impaired patients collected using a similar protocol. The population mean showed a consistent improvement in DVA performance during the two-week postflight recovery period. These data probably underestimate the DVA decrements experienced by crews during and immediately after landing.

Changes in dynamic visual acuity also contribute to functional changes (on the ground) in patients with vestibular disorders (71). For various reasons, physicians often caution patients with vestibular disorders against driving (38). One such patient, referred to a rehabilitation program, specifically identified an inability to stabilize visually the car's instrument panel as a reason for self-limiting driving (H. Cohen, personal communication). Clark & Rupert (33) report on a case study involving a student naval aviator with a similar complaint. Turbulence caused the aviator to become unable to see the instrument panel clearly. Testing revealed that the student had defective vestibulo-ocular reflex (VOR) function. As a result, his eye movements were not able to compensate adequately for the motions of his body in turbulent conditions.

No decrements in visual acuity should be expected under conditions where a non-moving person is visually fixating a stationary target (see *Static Visual Acuity* above). However, vestibular impairment can restrict a person's ability to make the appropriate eye movements that are necessary to compensate for movements of the head. Inappropriate or inadequate ocular compensation results in an inability to stabilize the visual image on the retina. It has been shown that for values above 2°/sec, increases in retinal slip velocity are accompanied by decreasing visual acuity (43). This relationship between ocular compensation and acuity has led to attempts to use measures of dynamic visual acuity (DVA) as a diagnostic tool for identifying vestibular dysfunction (92, 163, 164, 174). In these studies, subjects' visual acuity was assessed during periods of self-motion. Regardless of whether the self-motion was generated by voluntary head rotations or passive whole-body rotations, the results indicated that DVA was capable of differentiating between the control subjects and the patients known to have vestibular deficits.

Studies Demonstrating Decrements in Eye-Hand Coordination Performance

Eye-hand coordination skills are also critically important to performing piloting tasks and controlling other vehicles and complex systems. Reaching to switches on instrument panels, smoothly guiding the trajectory of a flight- or ground-based vehicle, and carefully positioning the end-effector of a robotic arm are some of the tasks requiring high levels of eye-hand coordination. While not studied as intensively as oculomotor performance, a number of studies of eye-hand coordination have been performed during space flight missions. The following subsections summarize some of the key evidence supporting eye-hand control performance decrements associated with space flight.

Control of Aimed Arm Movements When astronauts first encounter an altered gravity environment, arm movements are often inappropriate and inaccurate (52, 81, 120). During the Neurolab Space Shuttle mission (STS-90), Bock and co-investigators (20) performed an experiment in which subjects pointed, without seeing their hands, to targets located at fixed distances but varying directions from a common starting point. Using a video-based technique to measure finger position they found that the mean response amplitude was not significantly changed during flight, but that movement variability, reaction time, and duration were all significantly increased. After landing, they found a significant increase in mean response amplitude during the first postflight session, but no change in variability or timing compared with preflight values. In separate experiments, Watt (180, 181) reported reduced accuracy during space flight when subjects pointed to memorized targets. This effect was much greater when the hand could not be seen before each pointing trial. When subjects pointed at memorized locations with eyes closed, the variability of their responses was substantially higher during space flight than during control sessions on Earth. In other studies (14, 136), the investigators found that when crewmembers on the Mir station pointed to targets with eyes open, variability and mean response amplitude remained normal, but the movement duration increased by 10 to 20% over the course of the mission (flight day 2-162).

Reaching and Grasping Thornton & Rummel (172) showed that basic tasks such as reaching and grasping were significantly impaired during the Skylab missions. Later, Bock *et al.* (19, 21-24) investigated pointing, grasping, and isometric responses during brief episodes of changed gravity, produced by parabolic flights or centrifugation. These experiments provided converging evidence suggesting that during either reduced or increased gravity, the mean amplitude of responses is larger than in normal gravity, while response variability and duration remains unchanged. During the Neurolab Space Shuttle mission, Bock *et al.* (20) found that the accuracy during flight of grasping luminous discs between their thumb and index fingers was unchanged from preflight values, but task performance was slower.

Manual Tracking Changes in the ability of crewmembers to move their arms along prescribed trajectories have also been studied in space. For example, Gurfinkel *et al.* (66) found no differences in orientation or overall shape when crew members with eyes closed drew imagined ellipses oriented parallel or perpendicular to their long body axes. In another study, Lipshits *et al.* (94) examined the ability of crewmembers to maintain a cursor in a stationary position in the presence of external disturbances. They found no performance decrements when the disturbances were easily predictable. However, in follow-on experiment using more complex disturbances, Manzey *et al. (99, 100)* found that tracking errors were increased early in flight, but gradually normalized within 2-3 weeks of exposure to the space environment. Later, Sangals *et al.* (162) reported a series of step-tracking experiments conducted before, during, and after a three-week space flight mission to assess the effects of prolonged microgravity on a non-postural motor-control task. Task performance accuracy was affected only marginally during and after flight. However, kinematic analyses revealed a considerable change in the underlying movement dynamics: too-small force and, thus, too-low velocity in the first part of the movement was mainly compensated by lengthening the deceleration phase of the primary movement, so that accuracy was regained at its end. They interpreted these observations as indicating an underestimation of mass during flight. No reversals of the in-flight changes (negative aftereffects) were found after flight. Instead, there was a general slowing down, which could have been due to postflight physical exhaustion. Bock *et al.* (20) reported data from another experiment during the Neurolab Space Shuttle mission, where subjects tracked with their unseen finger a target moving along a circle at 0.5, 0.75, or 1.25 cycles/s. Subjects' response paths were found to be elliptical rather than circular. They found that the variability of finger positions about the best-fitting ellipse was significantly higher than preflight during the first in-flight session, and that responses lagged significantly behind the target during the highest target speed condition. Performance normalized later during flight, but deficits, albeit less pronounced, reappeared during the first two postflight test sessions. It should be noted that response slowing and increased variability were limited to the first in-flight session for the tracking paradigm, but were most pronounced during later in-flight sessions for the pointing paradigm.

Force Discrimination and Control During a MIR station mission the ability of a cosmonaut to reproduce several positions of a handle from memory was tested. The accuracy with which the handle was set to a given position was reduced; however, the temporal parameters of the movement and the number of discernable handle positions did not change (94, 154).

Fine Motor Control Campbell *et al.* (31) evaluated the feasibility of survival surgery performed on rats during the Neurolab Shuttle mission. Craniotomy, leg dissection, thoracotomy, laminectomy, and laparotomy were performed as a part of physiological investigations. Surgical techniques successfully demonstrated in rats during space flight include general anesthesia, wound closure and healing, hemostasis, control of surgical fluids, operator restraint, and control of surgical instruments. Although the crew noted no decrement in manual dexterity, the operative time was longer compared with the ground experience due to the need to maintain restraint of surgical supplies and instruments. In another study, Rafiq *et al.* (145) measured the effect of microgravity on fine motor skills by investigating basic surgical task performance during parabolic flight. They found that forces applied to the laparoscopic tool handles during knot tying were increased force while knot quality was decreased during flight compared with ground control sessions. Also, Panait *et al.* (135) studied the performance of basic laparoscopic skills (clip application, grasping, cutting, and suturing) during parabolic microgravity flights. When compared with one gravity performance, they found that there was a significant increase in tissue injury and task erosion and a decreased trend in the number of tasks successfully completed.

Dual Tasking and Manual Performance Manzey *et al.* (99, 100) investigated motor skills in space under dual-task conditions. They found interference between a compensatory tracking task and a concurrent memory search task to be greater in space than on Earth. The elevated interference was greatest early in flight, but gradually normalized, reaching the preflight baseline only after about nine months in orbit. In one of these studies, Manzey *et al.* (100) also found that task interference was independent of the difficulty of the memory search task, suggesting that the critical resources affected were probably not those related to memory, but rather those pertinent to motor programming (both tasks required an immediate motor response).

Laboratory tasks might underestimate the actual deficits since they differ from a real-life scenario in a number of ways. For example, the slowing of aimed arm movements was 10-30% in experimental tasks, but was up to 67% during routine activities on Skylab as analyzed using time and motion studies (90). Degradation of performance may be exacerbated in part due to postural instability, which may not play a role when a pilot controls a landing while strapped into a seat, but may have a greater impact if landing is performed while standing like during the Apollo lunar landings.

Studies Demonstrating Decrements in Spatial Orientation Perception

Spatial disorientation has been one of the most frequently studied aspects of sensory-motor adaptation to and from space flight. Returning crewmembers report that the most overt physiological phenomena associated with space flight are inversion illusions at main engine cut off, occasional in-flight disorientation, early-mission motion sickness, and head-movement-contingent disorientation during entry and landing. These neuro-vestibular phenomena occur during and after G-level transitions, which, unfortunately, also correspond to mission phases where physical and cognitive performance are particularly critical for crew safety and mission success. Accurate perception of self-in-space motion and self-motion relative to other objects are critical to piloting, driving, and remote manipulator operations. A summary of the main findings follows.

Manual Control of Vehicle Translation and Tilt In studies performed immediately after two Spacelab missions, returning astronauts were seated on a rail-mounted sled, and asked to use a joystick to null a random linear disturbance movement along their interaural (6) and/or longitudinal (110) body axes. Four of the seven subjects tested showed improved postflight performance on the nulling task. Also, Merfeld (109) tested the early postflight performance of astronauts trying to maintain a flight simulator in an upright orientation in the presence of pseudorandom motion disturbances about a tilt axis located below their seat. On landing day, both subjects showed impaired ability to control their tilt in the dark, but displayed normal responses when visual motion cues were provided. Results confirm that returning crews have difficulty estimating their tilt orientation with respect to the gravitational vertical on landing day. The absence of change with visual cues shows that neuromuscular and fatigue factors were not major contributors to the effect. It is important to note that the subjects in these experiments all knew whether tilt or translation motions were possible. Subsequent experiments (137, 183) showed that when subjects must resolve tilt-translation ambiguities, and are naïve to the possible motion, large misperceptions of tilt could result (see Tilt-Translation and Tilt-Gain Illusions below).

Spatial Disorientation During Space Flight The literature on spatial disorientation events during space flight has been well-reviewed by Oman (122, 123). Numerous detailed firsthand accounts by astronauts and cosmonauts have also appeared (30, 39, 83, 93, 95, 127). Almost all crewmembers describe a transient somatogravic tumbling illusion or momentary inversion illusion upon reaching orbit, when main engine cutoff causes a rapid deceleration to constant orbital velocity. About 10% subsequently experience a sense of gravitational inversion that persists regardless of relative body orientation in the cabin, even with eyes closed. Persistent inversion illusions are thought to result from the combined somatosensory effects of headward fluid shift, and saccular otolith unweighting (115, 128).

Far more universal is the "visual reorientation illusion" (VRI), first described by astronauts on the Skylab and Spacelab-1 missions (39, 128). When crew float about in the cabin, they often experience a spontaneous change in the subjective identity of surrounding surfaces, such that the "*surface beneath my feet seems somehow like a floor*." Oman *et al.* (39, 122, 123, 128, 129) noted that astronauts must orient with respect to a vehicle frame of reference defined by local visual vertical cues. However, architectural symmetries of the cabin interior typically define multiple "visual vertical" directions, usually separated by 90°. The Earth can provide yet another visual reference frame when viewed through cockpit windows or while spacewalking. There is a natural tendency to perceive the subjective vertical as being aligned with the head-foot axis, generally referred to as the "idiotropic" effect (116). Which visual reference frame the observer adopts thus depends strongly on relative body orientation and visual attention. VRI occur when the perceived visual vertical reference frame is not aligned with the actual, so that, for example, the overhead surface is perceived as a deck. Recent data from animal experiments in parabolic and orbital flight (123, 169) suggest that the VRI surface identity illusion physiologically corresponds to a realignment of the two-dimensional plane that limbic neurons use to code direction and location (see *Physiological Basis for Spatial Disorientation* below). When VRI occur, crews lose their sense of direction with respect to the entire vehicle, and reach or look in the wrong direction for remembered objects. Susceptibility to VRI continues through the first weeks in space, and occasional illusions have been reported after many months on orbit. Strong sensations of height vertigo have been described during spacewalks. These might reflect sudden changes in the limbic horizontal frame of reference from the spacecraft to the surface of the Earth.

VRI can also occur on Earth, but reorientations usually occur only in yaw perception about the gravitational axis (e.g., when we emerge from a subway and discover we are facing in an unexpected direction). VRI about Earth-horizontal axes have been created using tumbling rooms and virtual reality techniques. For example, Howard and colleagues (70, 76, 77, 80) have shown that the direction and strength of visual vertical cues depend on field of view, the relative orientation of familiar gravitationally "polarized" objects, and the orientation and symmetry of surfaces in the visual background. Single planar surfaces or the longer surface in a rectangular room interior were most frequently identified as "down." Oman (123) has noted that prior visual experience and knowledge of the specific environment are also important factors. Even when VRI do not occur, the visual verticals of adjacent or docked spacecraft modules are often incongruently aligned. Astronauts typically orient to the reference frame of the local module, and significant cognitive effort is required to sort out these multiple vehicle frames of reference. Using virtual reality simulations, Oman and colleagues (4, 5, 123) have recently shown that subjects remember the interiors of each module in a canonical, visually upright orientation. When performing tasks that require subjects to interrelate different reference frames, additional time is required and workload imposed. The fastest responses occur when module verticals are congruently aligned. Significantly greater time is required to perform simulated emergency egress navigation tasks when module visual vertical reference frames are incongruently aligned (125).

Physiological Basis for Spatial Disorientation The physiological basis of spatial orientation perception became better understood with the discovery in rat and primate limbic systems of place cells that code the direction the animal is facing, independent of head movement. Also discovered were grid and place cells that code various attributes of location relative to visual landmarks (184), analogous to a map of the local environment. All three classes of cells respond in a navigation coordinate frame normally defined by the plane of locomotion, even in 0 G and hypergravity (86, 169). How larger (geo) scale environmental knowledge is coded is not yet understood, but clinical evidence from patients with poor geospatial abilities suggests that these same limbic structures at least participate.

Tilt-Translation and Tilt-Gain Illusions Arguably the greatest space flight-related challenge to the human internal navigation system results from the ambiguities between tilt and translation stimuli. Albert Einstein was the first to postulate "the complete physical equivalence of a gravitational field and a corresponding acceleration of the reference system" (47). According to his equivalence principle, linear accelerations resulting from translational motions are physically indistinguishable from linear accelerations resulting from tilts with respect to gravity because the forces are identical in nature. The ability of the central nervous system to resolve tilt-translation ambiguities is critical to providing the spatial orientation awareness essential for controlling activities in everyday life.

Two hypothetical mechanisms that have been proposed for resolving tilt-translation ambiguities are frequency segregation and multi-sensory integration. The frequency segregation hypothesis suggests that low frequency linear accelerations are interpreted as tilt and high frequency accelerations as translation (101). This hypothesis appears consistent in principal with the response dynamics of the different primary otolith afferents (50, 140), secondary processing of otolith input in the vestibular nuclei (85, 187), and also with natural behavior (142). The multi-sensory integration hypothesis, on the other hand, suggests that the brain must rely on information from other sensors, such as canals and vision, to correctly discriminate between tilt and translation (2, 63). More specifically, it suggests that the brain learns to anticipate a sequence of sensory feedback patterns for any given movement. This hypothesis generally involves the use of "internal models," or neural representations of physical parameters, and combines efferent and afferent information to resolve sensory ambiguity (45, 58, 121, 189, 197).

Although multi-sensory integration and frequency segregation are typically posed as competing hypotheses, they are not mutually exclusive. The segregation of otolith-ocular responses as a function of frequency has been clearly demonstrated (e.g., 132). Yet one implication of frequency segregation is that there must be a mid-frequency crossover region where it is difficult to distinguish tilt from translation. Paige & Seidman (133) reported that the crossover frequency is approximately 0.5 Hz in primates, and Wood (186) suggested that it occurs at about 0.3 Hz in humans. Multi-sensory integration may play a critical role near the crossover frequency.

Among the factors that facilitate sensory-motor adaptation, active voluntary motion may be one of the most important (182). Performing visual tasks with the intent to override vestibular input may also catalyze adaptation (64). Most sensory conflict theories related to sensory-motor adaptation have been derived from the concept of 'efference copy' which states that there are predicted sensory feedbacks for any given motor action (148, 178). Head movement kinematics on Earth yield invariant unique patterns of canal and otolith signals irrespective of other sensors (65). During adaptation to altered gravito-inertial environments, though, new patterns of sensory feedback must become associated with head movements to reduce sensory conflict. The observation that some astronauts tend to restrict head-on-trunk movements on orbit, preferring to rotate more from the waist than the neck, reflects an adaptive change in motor strategy that might further contribute to motion sickness (179) and post-flight postural and gait dysfunction (18). This is also a common symptom of patients with vestibular hypofunction.

Following adaptation to weightlessness during space flight, the reappearance of gravito-inertial force during reentry produces strong head movement-contingent vertigo, oscillopsia (illusory motion of the entire visual scene), and reduced visual acuity. Crewmembers train themselves to limit head movements, but some make deliberate small movements in an effort to accelerate readaptation. The illusory sensations persist for at least several hours after flight. During the initial recovery, it is often reported that 1-G feels like three. Crewmembers typically exit the Shuttle using a wide gait, and a few long duration crews have been simply unable to stand or walk unaided for several hours or longer. Crews typically say that when they tilt their heads, they feel that the "gain" of their head tilt sensation is increased, as if their head had rotated farther than expected. Typical pilot comment: "*That really tumbled my gyros.*" The sensation is thus reminiscent of the conventional hypergravic G-excess illusion. Other returning astronauts describe a transient sensation of horizontal or slightly upwards linear translation as a result of head tilt (69, 138, 153). One of the most common post-flight illusions is of perceived translation, either of self or surround, during a tilting motion (68). In one of the first post-flight experiments to investigate this phenomenon, Reschke and colleagues (138, 155) used a parallel swing to provide horizontal (interaural axis) translation and/or roll rotation about the head naso-occipital axis. All six astronauts participating in this study reported an increase in perceived lateral translation during passive roll rotation after flight.

On the basis of these observations, and similar ones reported by Young *et al.* (194), the otolith tilt-translation reinterpretation hypothesis (OTTR) was proposed (138, 194). The OTTR hypothesis is based on the premise that interpreting otolith signals as indicating tilt is inappropriate during space flight. Therefore, during adaptation to weightlessness, the brain reinterprets otolith signals as indicating translation only. Other post-flight observations that have been used to support the OTTR hypothesis include decreased postural stability (75, 134) and decreased static ocular counterrolling (177, 195). Relevant to driving tasks on sloped terrains, it is interesting to note that performance during roll-tilt closed-loop nulling tasks is decreased for several days post-flight (107), while performance during translation closed-loop nulling experiments appears to be improved (7).

An alternative hypothesis proposed by Guedry *et al.* (65) suggests that rather than a reinterpretation of otolith signals, adaptation to space flight might involve 'shutting down' the search for position (tilt) signals from the otolith system in order to avoid vestibular conflict. This is based on the observation that on Earth the initial head position relative to gravity before a head turn foretells the unique combination of canal and otolith signals that will occur during the turn. The absence of a meaningful initial position signal from the otoliths on orbit may therefore be functionally disruptive, and eventually neglected. Guedry's hypothesis (65) also explains the post-flight tilt-translation disruptions described above, as well as the increased immunity to Coriolis stimuli observed following the Skylab missions (57).

Differences between active and passive motions may help explain some of the apparently contradictory observations regarding post-flight tilt-translation disturbances. For example, Golding *et al.* (56) observed striking differences in motion sickness sensitivity between active and passive tilts. It is likely that the new 'expected' patterns of sensory cues adopted during head tilts on orbit will differentially influence responses during reentry depending on whether the motion is self-generated.

Merfeld and colleagues (108, 111, 112) have provided additional insight into the origin and relationships between the post-flight Tilt Gain and OTTR illusions. Merfeld (108) noted that the OTTR hypothesis assumes that the utricular otolith mediates all tilt sensation, and that if otolith cues were simply reinterpreted as linear acceleration, a sustained head tilt should produce a sustained acceleration sensation–not what is usually observed. He hypothesized that both types of illusions could result from a change in the effect of semicircular canal cues on estimating transient rotations of the direction of "down" relative to the head. Unless the CNS estimate of angular velocity is aligned with the estimated direction of gravity, a conflict occurs. His hypothesis (111), known as the Rotation Otolith Tilt-Translation Reinterpretation (ROTTR) hypothesis, suggests that the CNS resolves this conflict by rotating the direction of its internal estimate of gravity at a rate proportional to the vector cross product of the estimated angular velocity and gravity vectors. These rate constants determined the dynamics of the resulting illusion.

Tilt-translation illusions can occur during spacecraft pitching or rolling maneuvers, even if the pilot's head remains stationary relative to the cockpit, and could lead to in incorrect manual control responses. For example, a Tilt Gain illusion might result in an under-response to a Shuttle wing drop, a sensation that a wind gust was pushing the nose up unexpectedly, resulting in under-rotation during the critical landing flare maneuver. An OTTR illusion might produce an over-response to a wing-drop, and perhaps the sensation that a gust had suddenly pushed the Shuttle off runway centerline. One implication of ROTTR theory is that the tendency toward Tilt Gain or OTTR illusions may be a personal characteristic. If so this could account for the diversity in the anecdotal descriptions by astronauts. Unfortunately, there are as yet no systematic longitudinal clinical data on the direction and strength of post-landing head tilt illusions in the Shuttle Program.

Two separate human experiments conducted on orbit by Clément *et al.* (36) and Reschke et al (151) investigated the effects of sustained linear accelerations during eccentric rotation created by short-radius centrifuges. Interestingly, subjects reported no sense of translation in either experiment during the constant velocity centrifugation. Reschke et al (151) exposed subjects to 0.2 G_z at the head during 60 s of constant velocity, which was insufficient to provide a vertical reference (12), possibly because of the opposing G-gradient along the trunk and legs and/or the relatively small resultant force level (114). Clément *et al.* (36) exposed subjects to greater force levels (0.5 G_y and 1.0 G_z) for up to 5 min. These forces did provide a vertical reference on orbit, with subjects perceiving roll-tilt when the resultant force was directed along the interaural axis, and inversion when the resultant force was directed towards the head (36). Ocular counterrolling was also unchanged during this experiment (117).

Physiological Basis for Tilt-Translation and Tilt-Gain Illusions Some evidence exists that provides insight into the physiological basis of these illusions. For example, in a series of rodent experiments, Ross and colleagues (158-161) showed increased numbers of synapses in type II hair cells of the utricular maculae during and just after space flight. The findings of increased synaptic plasticity are consistent with the human behavioral studies suggesting an increased gain of the otolith organs. These findings were also supported by an experiment performed by Boyle *et al.* (28) aboard the Neurolab mission, in which the primary utricular afferent information was shown to be highly potentiated (up-regulated) during the first few hours after space flight in oyster toadfish (*Opsanus tau*) subjected to linear translations in various planes. These data were similar to those reported by Reschke *et al.* (152), who found an enormous potentiation of the monosynaptic Hoffman (H-) reflex response early after flight in human subjects from the Spacelab-1 mission subjected to linear translational acceleration stimuli. This H-reflex response, which is modulated by descending signals from the vestibular otolith organs and normally aids in preparing the anti-gravity muscles for stable landing following a jump (or fall), had completely disappeared in these same subjects by the sixth flight day of the mission. Further evidence was obtained by Holstein *et al.* (74), who found in rodents flown aboard the Neurolab mission ultrastructural signs of plasticity in the otolith recipient zone of cerebellar cortex (nodulus), an area thought to be critical for motor control, coordination, timing of movements, and motor learning. Rats flown for 5-18 days in the Russian Cosmos Biosatellite Program also showed morphological changes in neural structure, including decreased lengths in dendrites directed from cells in the reticular formation toward structures in the vestibular nuclei and morphological changes in cerebellar structures including mossy fiber terminals in the granular layer of the nodular cortex (89). Pompeiano (141) also studied rodents flown aboard the Neurolab mission. He found biochemical evidence of plasticity (expression of the immediate early gene *c-fos* and presence of *fos*-related antigens) in multiple regions of the brain, including the vestibular nuclei, which play a role in controlling posture and eye movements, the nucleus of the tractus solitaries (NTS), which is involved in regulation of cardiovascular and respiratory function, the area postrema, which plays a role in motion sickness, the amygdala, cortical and subcortical areas involved in body orientation and perception, and the locus coeruleus, which is involved in regulation of the sleep-wake cycle.

Studies Demonstrating Decrements in Cognitive Function

Controlling vehicles and other complex systems can place high demands on cognitive and psychomotor functions. Space flight might affect these functions through direct microgravity effects (such as those described in the preceding sections) or through stress effects associated with sleep loss, workload, or the physical and emotional burdens of adapting to the novel, hostile environment (84). Kanas & Manzey (84) provide a good overview of the relevant evidence. As should be clear from the evidence presented above, space flight induces many of the hallmarks of a (reversible) vestibular lesion. Cognitive deficits, such as poor concentration, short-term memory loss, and inability to multi-task occur frequently in patients with vestibular abnormalities (78, 79). Hanes & McCollum (67) have recently published a thorough review of the literature suggesting broader interactions between vestibular and cognitive function (including oculomotor, motor coordination, and spatial perception/memory effects similar to those described above) and demonstrating a physiological basis through observations of neuronal projections from the vestibular nuclei to the cerebral cortex and hippocampus. These results suggest that cognitive abilities may be most compromised during landing, particularly if an off-nominal event occurred that had not been recently well-rehearsed.

B. Ground-Based Evidence

Few robust ground-based models are available for simulating/observing the impacts of space flight on a crewmember's ability to maintain control of vehicles and complex systems. Where relevant ground-based studies exist, they have been included in the discussions presented above. However, understanding ground-based aviation experiences with spatial disorientation may be useful to identifying and mitigating space flight related issues with spatial disorientation. Thus, this section reviews studies on the effects of spatial disorientation on aircraft control.

Spatial Disorientation in Aviation Spatial Disorientation (SD) is traditionally defined as a "*failure to correctly perceive attitude, position, and motion of the aircraft*" (11), as displayed on the aircraft's primary attitude and flight control displays (53). A history of aviation SD research, a taxonomy of the classic SD illusions, an explanation of the underlying physiology, and data on incidence of SD related accidents have been well-reviewed by Previc & Ercoline (143), Gillingham *et al.* (53, 54), and Young (191). Classic SD (e.g., somatogravic illusions, leans, G-excess illusions, inversion illusions, or Coriolis illusions) can result from unusual vestibular stimulation or from sparse or misleading visual cues (false horizons, ambiguous size, or surface slant cues). SD has been further categorized (54) as Type I (unrecognized), Type II (recognized), or Type III (incapacitating). Type 1 SD is the most insidious because the pilot is unaware the aircraft is in a dangerous state.

Spatial disorientation remains an enduring problem in aviation. Surveys consistently indicate that a majority of pilots have experienced significant SD, many more than once. Pilots spend hours training, hoping that when SD occurs they will recognize it and be able to fly through it using their instruments. Incidence of SD depends on the type of flying and weather conditions. The likelihood that SD will create an accident goes up when flying at low altitude, since there is less time to recognize and recover. In US general aviation, SD is a factor in 15% of fatal accidents, a rate of one every 100,000 flying hours (NTSB 2007). Hence there is one fatal SD related accident approximately every week. In US scheduled airline flying, most of which is at high altitude and on autopilot, the SD rate is far lower, though, as discussed below, controlled flight into terrain during approach remains a problem. For similar reasons, in military flying, SD rates are higher in fighter/attack aircraft and helicopter operations than in military transport flying. In the US Air Force, the overall SD rate is 0.5 per 100,000 flying hours. SD was a factor in 14% of all major accidents, and insufficient or misleading visual cues contributed to 61% of these (73, 96). Many military aircraft HUD displays automatically declutter to better support recognition and recovery of extreme attitudes. In US Army helicopter operations, most of which take place at low altitudes, the overall SD rate has been about 3 per 100,000 hours. However, the rate rises by a factor of five at night, and by 20 when night vision goggles are used (29, 41, 46). Lack of reliable visual references has been the most frequent cause of helicopter SD fatalities, typically due to rain, fog, blowing snow or dust during landing.

There is evidence from flight simulator experiments that instrument flying experience and recency (within 2 weeks) helps pilots "fly through" disorienting transients created using galvanic stimulation of the vestibular system (98). However, applying such stimulation to pilots flying visual approaches can trigger pilot induced oscillations (97).

Geographic Disorientation and Terrain Awareness A second class of accidents and incidents are caused by "Geographic Disorientation," defined as the failure to recognize and/or maintain the desired position relative to the external ground and airspace environment (3). Common examples include becoming lost in the air or on the ground and then straying into prohibited airspace, landing at wrong airport, or taking off, landing, or intruding into an inappropriate runway, causing collisions or overruns. Cockpit map displays have reduced these accidents, but do not (yet) depict runway/taxiway details.

Loss of "Terrain Awareness" is almost always a factor in Controlled Flight Into Terrain (CFIT) accidents, where the pilot unintentionally flies into terrain, usually during the approach-and-landing phase. Ground proximity warning systems (e.g. GPWS, MSAW), mandated since the 1970s in civil transport aircraft, have reduced the number of CFIT accidents, but they still account for a third of all fatal accidents in this sector over the past decade (25). CFIT can result from classic spatial disorientation, but more commonly results from loss of terrain awareness due to preoccupation with other tasks, or incorrectly setting and/or inappropriately trusting the autopilot. Electronic cockpit map displays highlighting nearby terrain (e.g. TAWS) and "synthetic vision" backgrounds for attitude indicators, depicting a virtual "out the window" view are expected to reduce CFIT incidence.

Because the classic definition of spatial disorientation does not include Terrain Awareness or Geographic Disorientation, CFIT and geographic disorientation accidents are typically only categorized by investigators as due to "Loss of Situational Awareness." At the most general level, Situation Awareness (SA) is defined as perception of elements defining a mental model of the current situation, comprehension of their meaning, and projection of their future status (49). Obviously, there are many dimensions to SA, including all elements of spatial knowledge, as well as awareness of traffic, weather, autopilot mode, fuel, system, and weapon status, etc. The more general SA concept has proven useful in understanding many types of accidents, partly because it emphasizes the importance of "confirmation bias" in attention, perception, and decision-making. Classic spatial disorientation accidents should also be properly co-coded as loss of situation awareness accidents (144), but traditionally are not.

Overall, one concludes that large transport aircraft operations are relatively safe – less than one spatial disorientation related accident every 10^6 approaches. However, in other aviation segments, where more of the flight is conducted at low altitude, in bad weather, and/or using sensory aids, the fatal accident rate rises by an order of magnitude or more.

II. COMPUTER-BASED SIMULATION INFORMATION

While there are few robust ground-based models available for experimental investigations of the impacts of space flight on a crewmember's ability to maintain control of vehicles and complex systems, many computer-based models of the vestibular system and sensory-motor control have been developed. Since these may be useful in simulating and/or predicting the impacts of physiological adaptations on operational performance, particularly under off-nominal conditions, a brief review of the relevant aspects of the field is provided in this section. Before they can be used in design and verification, though, these (and other) models must be quantitatively validated and certified using targeted empirical studies.

<u>Models of Vestibular Function and Spatial Orientation</u> Vestibular neuroscientists have developed quantitative mathematical models for semicircular canal and otolith function, eye movements, and central nervous system (CNS) estimation of angular and linear motion perception. For example, Fernandez & Goldberg (51) modeled the firing frequency f_i of individual semicircular canal afferents using a linear transfer function model of the form $f_i(s)/\omega(s) = s^2 K_i [(K_r s +1)/(\tau_d s + 1)(\tau_c s +1)(\tau_a + 1)]$, where ω is the component of head angular velocity in the canal plane, K_i is mid frequency gain, K_r is high frequency gain, τ_d and τ_c are the time constants of endolymph flow drag development and cupula-endolymph return (62, 129), and τ_a is a time constant describing neural adaptation (193).

Young (196) originally suggested that the CNS functions like an adaptive (Kalman) filter when combining sensory cues, and introduced additional dynamics into vestibular responses due to these central processes. Adapting inertial guidance theory, Young and colleagues (188, 192, 194) noted that laws of physics dictate that the body's graviceptors respond to the net gravito-inertial specific force ($\mathbf{f} = \mathbf{g} - \mathbf{a}$), the physical quantity tracked by a pendulum or measured by a linear accelerometer (where $\mathbf{a}$ = linear acceleration vector and $\mathbf{g}$ = gravitational acceleration vector). A variety of different orientations and accelerations can cause the same graviceptor stimulus. The CNS must therefore use other cues to distinguish the components caused by gravity from those caused by linear acceleration. The CNS may estimate linear acceleration by maintaining an internal estimate of the direction and magnitude of ($\hat{\mathbf{g}}$) and subtracting off the graviceptor cue vector ($\hat{\mathbf{a}} = \hat{\mathbf{g}} - \mathbf{f}$). The direction of down, $\hat{\mathbf{g}}$ is estimated at low frequencies based on the average direction of graviceptor cues, $\mathbf{f}$, and also visual cues, if available. Visual inputs are angular and linear velocity of the visual surround with respect to the observer. At high frequencies, semicircular canal cues and body movement commands are used. If the direction of $\hat{\mathbf{g}}$ is misestimated, dramatic misperceptions of orientation and linear acceleration can result.

Although "optimality" of the human observer (in the Kalman sense) has since been discounted, the notion remains widely accepted that the CNS functions as an "observer," in the control engineering sense (27), estimating head orientation based on internal representations of the direction of gravity and sensory organ dynamics. Others have elaborated CNS observer-based models for semicircular canal-otolith interaction. For example, Raphan *et al.* (147), Robinson (156), and Merfeld *et al.* (111) developed influential observer class models for CNS estimation of head angular velocity and tilt, now often referred to as "central velocity storage" theories. Merfeld's contemporary models for canal-otolith cue interaction in "down" estimation (108, 112) successfully predict canal-otolith cue interaction in a variety of experimental situations. They are now widely utilized in research and the diagnosis of clinical vestibular disorders. These models have occasionally been applied to aircraft accident investigation, albeit in a limited way, since they do not (yet) incorporate effects of visual cues, and data on aircraft accidents is frequently lacking.

Models of Manual Control Performance Manual Control theory was originally developed in the 1960s, when feedback control engineers sought to analyze and predict the performance of humans in control loops, and describe both the human (the operator) and the controlled system (the plant) within the same mathematical framework. The premise was that human operator performance could be approximated well using a "describing function." Both compensatory tasks (where the operator sees only an error signal) and pursuit tasks (where both the goal and plant outputs are available) have been modeled this way. A simple and widely used principle is the "crossover model" (104), which posits that the operator will instinctively adopt an appropriate control strategy such that at the open loop transfer function of the operator and plant taken together resembles that of a simple integral process and a time delay in the region of the crossover frequency. The operator can perceive the rate of change of plant output, and create anticipatory phase lead that counteracts phase lags due to the plant. If the plant is a vehicle, vestibular motion cues allow the operator to improve performance by creating additional phase lead. However, the operator's transfer function is constrained. Some effective time delay is always present due to perceptual, cognitive, and muscle activation effects. Also, operators cannot respond to the second or higher derivatives of plant output. The crossover model structure and parameter values thus quantify the operator's control strategy. The model also has important emergent properties: It predicts manual control gain and bandwidth limits. It also explains why humans cannot successfully stabilize higher than second order integral plant dynamics, unless the operator is able to monitor intermediate system outputs, in effect transforming the task into concurrent (multi-loop) lower order tasks. This is why an operator cannot successfully stabilize a hovering lunar lander or a helicopter (approximately triple integral plants) over a landing spot without reference to a real or artificial horizon, and why motion cues can have a dramatic effect on controlling marginally stable plants (165, 190). The crossover model has been extended to multi-loop control and validated across a wide variety of plant dynamics, and extensively applied in many domains, particularly in the area of vehicle handling quality standards (192).

In the late 1960s, newer estimation and optimal control concepts, such as the Kalman observer and controller, were used to extend manual control theory. The optimal control model (10) posited that the human observer's control strategy utilized an internal dynamic mental model for the plant, and it weighted feedback information based on prior knowledge of uncertainties. (Concurrent efforts by neuroscientists led to the present generation of Observer Theory models for orientation and sensory conflict in motion sickness described earlier.) Early applications included helicopter hovering and attention sharing. Results demonstrated the importance of vestibular motion cueing (9, 42).

When performing maneuvers such as flaring an aircraft on landing, a highly skilled human operator uses a "precognitive control strategy," and generates open loop, preprogrammed commands based on a mental model of the plant. The preprogrammed command accomplishes most of the maneuver, but the operator completes the task by switching back to conventional compensatory manual control for final error reduction. The Shuttle landing flare is an example of a task accomplished using precognitive control (8). Landing performance depends critically on proper timing of the preprogrammed manual flare command, and correct estimation of the aircraft state at that moment. Incorrect precognitive manual commands result in greater need for subsequent compensatory error reduction. After the flare, the pilot exerts "tight" control over aircraft altitude and altitude rate in order to achieve a smooth touchdown, employing relatively high control gain. Because the Shuttle flight control system has inherent phase delays and rate limits, excessively large pilot control gain can make the combined pilot-vehicle system unstable, and trigger pilot induced oscillations (104). At the time it was not generally recognized that misperceptions of vehicle pitch attitude and rate could also potentially cause over control and pilot induced oscillations (PIO), but they were detected during the Shuttle Enterprise Approach and Landing Test flight test program, where disorientation was presumably not a factor. Since control system delays could not be eliminated, a stopgap solution was to detect large oscillatory control stick commands using a suitable nonlinear filter, and adaptively reduce pilot control authority (167). Adaptively reducing control authority worked for "conventional" PIO. However, as described earlier, STS-3 subsequently experienced a PIO despite the PIO suppression filter. The only solution for disorientation induced PIO is to provide strong visual cues to pitch and pitch rate via a HUD, and restricting landings to conditions of good visibility. If the Shuttle were required to land in brownout/grayout conditions (e.g. as are Lunar Landers), PIO would be a continuing concern.

III. RISK IN CONTEXT OF EXPLORATION MISSION OPERATIONAL SCENARIOS

Sensory-Motor Standard

A sensory-motor standard has been drafted (NASA Standard 3001) for exploration class missions: "*Pre-flight sensory-motor function shall be within normal values for age and gender of the astronaut population. In-flight Fitness for Duty Standards depend on mission and high risk activities, and they shall be assessed using metrics that are task specific. Sensory-motor performance limits for each metric shall be operationally defined. Countermeasures shall maintain function within performance limits. Post-flight rehabilitation shall be aimed at returning to baseline sensory-motor function*." However, operational performance limits related to flight vehicle control (particularly for post-adaptation activities, such as rendezvous/docking and entry/landing), ground vehicle control (*e.g.*, Lunar or Martian rovers), and remote manipulator/teleoperation activities have not yet been established.

Risks During Piloted Landings

Piloting a spacecraft through entry and landing is one of the most difficult tasks associated with space flight. The consequences of failing to complete this task successfully could be catastrophic, resulting in loss of life, vehicle, or other assets. While all piloted landings from space have been successful to date, the evidence presented above suggests that the landing performance has been lower than desired for both the Shuttle and the Lunar Lander. To the (currently unknown) extent physiological adaptations play a role in these performance decrements, we can anticipate that the risk of failure will become much greater during Mars missions. There is strong evidence that the six-month outbound trip (without artificial gravity) will cause a much more profound sensory-motor adaptation to zero-G than occurs during a 1-2 week Shuttle mission. This will likely cause a more profound physiological response to the G-transition during entry/landing; however, the impact of the reduced amplitude (3/8 g vs. 1 g) of the transition is unknown. Furthermore, piloting recency will decrease from 1-2 weeks during the Shuttle program to approximately six months during a Mars mission, decreasing the probability that a pilot will be able to fly through any spatial disorientation that accompanies the G-transition. Even piloted landings on the Moon present some unique risks, owing to the effects of the novel gravitational environment on spatial and geographic orientation and the potential for lunar dust obscuring vision during critical phases of landing.

Risks During Rover Operations

The risk of performance failure (*i.e.*, loss of vehicle control) while driving an automobile is high for those having vestibular deficiencies and for those whose cognitive and/or sensory-motor functions are impaired by ethanol, fatigue, or certain medications. Crewmembers readapting to Earth-gravity following return from space flight exhibit similar performance decrements, and, as a result, are currently restricted from driving automobiles for a short time (2-4 days) after Shuttle missions and a longer time (8-12 days) after ISS missions. The impact of sensory-motor adaptations on driving rovers on either Moon or Mars is unknown. While the potential consequences of performance failure while driving a rover are less than those of piloting a space craft through entry and landing, the possibility of crew injury (or death) or loss of the rover exists, particularly in the vicinity of steep-sided craters. The duration of the initial adaptation period to the Lunar or Martian gravity environment is also unknown, and, while likely to be proportional to the time spent in zero-G transit, cannot be determined until it can be measured on the planetary surface. Thus, the amplitude and duration of increased risk during rover driving are currently unknown.

Risks During Rendezvous/Docking and Remote Manipulator System Operations

Apart from the Spektr incident, performance data on rendezvous/docking has so far eluded the authors. However, evidence provided above suggests that the incidence of performance failure during remote manipulator operations aboard the Shuttle and ISS has been fairly well characterized (at least operationally). There is no reason to suspect that performance of these zero-G operations will be any different from our ISS experience during an outbound transit to Mars. Thus, we would not expect the risk to increase. However, the risk impacts of an additional 18 months at Mars gravity followed by six months at zero-G during return transit are unknown, and may well lead to an unacceptable range.

Risks While Operating Other Complex Systems

The risk of performance failure during operation of any complex system is multi-factorial. However, operation of any system requiring good visual acuity, eye-hand coordination, (balance/locomotor skills for surface operations), spatial orientation, and/or cognition could be impaired by physiological adaptations to novel gravitational environments. The risk of impairment is generally greatest during and soon after G-transitions, but the amplitude and duration of the increased risk would need to be evaluated on a system-by-system basis.

Risks During Near-Term Missions

Despite programmatic guidance that this risk be considered low in priority for ISS and Lunar missions, there is significant evidence suggesting that the control of vehicles or complex systems is compromised after as little as a few days of exposure to spaceflight environments, and that severity increases with increasing exposure time (as might be expected for ISS stays and extended Lunar sorties). While these issues may be more severe for Mars missions without artificial gravity, significant risks remain quite real even for more standard ISS and Lunar operations. As the Columbia Accident Investigation Board (CAIB) report warned us repeatedly, a small number of successes without catastrophic failure (*e.g.*, a little over 100 Shuttle landings and 6 lunar landings) does not mean that risk, including human sensory-motor adaptation risks, can be ignored. The near misses reported above provide evidence in this regard. The architecture being employed for NASA's return to the Moon requires a much more challenging re-entry G-force and vibration regime than was used during Apollo. Indeed, any human control effort, even under nominal Orion re-entry/descent/landing scenarios, will likely be much more difficult than for Shuttle landings if this design remains. Furthermore, some of the off-nominal human interventions being contemplated may push human performance of a deconditioned crewmember beyond its absolute limit (*e.g.*, human backup roll control authority during a $5G_X$ re-entry after three weeks in space). Finally, the proper resolution of automation-human control authority decisions requires an objective and quantitative understanding of sensory-motor compromises. The risk of sub-optimal decisions in this regard has important ramifications for overall mission safety/reliability calculations. Thus, we recommend that this risk be considered high priority for all space flight mission scenarios.

IV. KNOWLEDGE GAPS

The authors, representing the NASA sensory-motor discipline team, have identified the series of knowledge gaps listed below. Each of them must be filled before this risk can be fully assessed and/or mitigated. The NASA Human Health and Performance Program has identified the following knowledge gaps as high priority for the sensory-motor discipline group:

1. There is little evidence correlating extant operational performance data (*e.g.*, extra-vehicular activity performance, remote manipulator system operations performance, rendezvous and docking performance, Shuttle landing performance, *etc.*) with clinical and/or research observations of post-landing sensory-motor performance decrements.

2. There is little experimental evidence demonstrating the effects of disorientation and/or inter-individual differences (*e.g.*, in spatial skills) on supervisory control (*e.g.*, space telerobotic operations and vehicle docking).

3. There is little experimental evidence demonstrating that flight-related changes in sensory-motor performance (reduced visual acuity, oscillopsia, head movement contingent tilt-translation/tilt-gain illusions, misperception of vehicle attitude and acceleration, unrecognized (type I) spatial disorientation) will cause decrements in and/or limitations to piloted landing of vehicles upon arrival at Mars.

4. There are no validated tests to define standards for acceptable operational performance ranges based on crewmembers' demonstrated post-flight sensory-motor capabilities and disabilities. Nor are there any validated tests to define the linkages between functional capabilities and physiological changes.

The Program has also identified the following, relevant knowledge gaps as lower priority for the sensory-motor discipline group, as they belong primarily to another discipline:

5. There is little experimental evidence demonstrating how flight-related changes in human supervisory/manual control (including vision, vestibular function, and spatial memory) should affect Constellation designs for lunar landings and rover operations (including geographic orientation, maintaining spatial orientation while maneuvering, visually verifying the suitability of the landing zone, and maintaining altitude, attitude, and terrain awareness during vertical descent and touchdown).

6. There is no validated multi-factorial cognitive risk assessment test to evaluate spatial skills and/or define acceptable ranges of cognitive and psychomotor performance.

7. Periodic in-flight medical examinations do not assess vestibular function.

V. CONCLUSION

A large body of sensory-motor and psychological research data obtained from space flight experiments over the past half-century demonstrates significant decrements in oculomotor control, eye-hand coordination, spatial orientation, and cognition during space flight missions. While these changes are most severe during and after G-transitions, the most crucial time for many critical operational tasks (e.g., landing and egress), only limited information is available to assess the operational impacts of these changes. Some of the operational observations are compelling, but are confounded by unknown environmental and engineering influences. Others appear to raise little concern, but the safety margins are difficult to estimate. During exploration missions, we can expect that most performance DURING G-transitions will be degraded further by the influence of extended time in flight (Mars missions), but the potential influence of extended time in hypogravity (Mars and Lunar missions) is unknown.

The true operational risks associated with the impacts of adaptive sensory-motor (and other) changes on crew abilities to control vehicles and other complex systems will only be estimable after the gaps (identified above) have been filled and we have been able to accurately assess integrated performance in off-nominal operational settings. While exclusive crew selection procedures, intensive crew training, and highly reliable hardware/software systems have likely minimized the operational impacts of these sensory-motor changes to date, the impacts of new mission and vehicle designs may offset some benefits.

Forward work in this area must account for the multi-factorial nature of the problem. While sensory-motor and behavioral (cognitive) disciplines clearly have roles to play, muscle (strength and endurance) and cardiovascular (orthostatic tolerance) disciplines also must be involved, as should human factors experts, training experts, vehicle designers, mission designers, and crewmembers. Mechanisms for facilitating cross-disciplinary investigations are only beginning to be established. Future success will clearly require more progress in these approaches.

ACKNOWLEDGEMENTS

The authors are indebted to Elisa Allen, Jody Cerisano, Julie Esteves, George Ford, and Laura Taylor for their efforts locating and assembling the evidence.

REFERENCES

1. **Andre-Deshays, C., I. Israel, O. Charade, A. Berthoz, K. Popov, M. and Lipshits.** Gaze control in microgravity. 1. Saccades, pursuit, eye-head coordination. *J. Vestib. Res.* 3:331-343, 1993.
2. **Angelaki, D.E., M.Q. McHenry, J.D. Dickman, S.D. Newlands, and B.J. Hess.** Computation of inertial motion: neural strategies to resolve ambiguous otolith information. *J. Neurosci.* 19:316-327, 1999.
3. **Antunano, M.J., and J.M. Hernandez.** Incidence of airsickness among military parachutists. *Aviat. Space Environ. Med.* 60:792-797, 1989.
4. **Aoki, H., C.M. Oman, A. and Natapoff.** Virtual-reality-Based 3D navigation training for emergency egress from spacecraft. *Aviat. Space Environ. Med.* 78:774-783, 2007.
5. **Aoki, H., C.M. Oman, A. Natapoff, and A. Liu.** The effect of the configuration, frame of reference, and spatial ability on spatial orientation during virtual 3-dimensional navigation training. In: *7th Symposium on the Role of the Vestibular Organs in Space Exploration*, edited by (ESTEC) ESAESTC. Noordwijk, the Netherlands: 2006.
6. **Arrott, A.P., and L.R. Young.** M.I.T./Canadian vestibular experiments on the Spacelab-1 mission: 6. Vestibular reactions to lateral acceleration following ten days of weightlessness. *Exp. Brain Res.* 64:347-357, 1986.
7. **Arrott, A.P., L.R. Young, and D.M. Merfeld.** Perception of linear acceleration in weightlessness. *Aviat. Space Environ. Med.* 61:319-326, 1990.
8. **Ashkenas, I.L., R.H. Ho, and G.L. Teper.** Analyses of Shuttle Orbiter Approach and Landing. *J. Guid. Control Dyn.* 6:448-455, 1983.
9. **Baron, S.** An Optimal Control Model Analysis of Data

from a Simulated Hover Task 1983.
10. **Baron, S., and D.L. Kleinman.** The human as an optimal controller and information processor. *Man Mach. Sys.* 10:9-17, 1969.
11. **Benson, A.J., and G.R. Barnes.** Vision during angular oscillation: the dynamic interaction of visual and vestibular mechanisms. *Aviat. Space Environ. Med.* 49:340-345, 1978.
12. **Benson, A.J., F.E. Guedry, D.E. Parker, and M.F. Reschke.** Microgravity vestibular investigations: perception of self-orientation and self-motion. *J. Vestib. Res.* 7:453-457, 1997.
13. **Benson, A.J., and T. Vieville.** European vestibular experiments on the Spacelab-1 mission: 6. Yaw axis vestibulo-ocular reflex. *Exp. Brain Res.* 64:279-283, 1986.
14. **Berger, M., S. Mescheriakov, E. Molokanova, and al. e.** Pointing arm movements in short- and long-term spaceflights. *Aviat. Space Environ. Med.* 68:781-787, 1997.
15. **Berthoz, A., T. Brandt, J. Dichgans, T. Probst, W. Bruzek, and T. Vieville.** European vestibular experiments on the Spacelab-1 mission: 5. Contribution of the otoliths to the vertical vestibulo-ocular reflex. *Exp. Brain Res.* 64:272-278, 1986.
16. **Berthoz, A., and G. Melvill Jones.** *Adaptive Mechanisms in Gaze Control*. Amsterdam: Elsevier Science Publishers, 1985.
17. **Bloomberg, J.J., and A.P. Mulavara.** Changes in walking strategies after spaceflight. *IEEE Eng. Med. Biol. Mag.* 22:58-62, 2003.
18. **Bloomberg, J.J., B.T. Peters, S.L. Smith, W.P. Huebner, and M.F. Reschke.** Locomotor head-trunk coordination strategies following space flight. *J. Vestib. Res.* 7:161-177, 1997.
19. **Bock, O.** Grasping of virtual objects in changed gravity. *Aviat. Space Environ. Med.* 67:1185-1189, 1996.
20. **Bock, O., S. Abeele, and al. e.** Human adaptation to rotated vision: interplay of a continuous and a discrete process. *Exp. Brain Res.* 152:528-532, 2003.
21. **Bock, O., K.E. Arnold, and B.S.K. Cheung.** Performance of a simple aiming task in hypergravity: I. Overall accuracy. *Aviat. Space Environ. Med.* 67:127-132, 1996a.
22. **Bock, O., K.E. Arnold KE, and B.S.K. Cheung.** Performance of a simple aiming task in hypergravity: II. Detailed response characteristics. *Aviat. Space Environ. Med.* 67: 133-138, 1996b.
23. **Bock, O., and B.S.K. Cheung.** Control of isometric force in hypergravity. *Aviat. Space Environ. Med.* 69:27-31, 1998.
24. **Bock, O., I.P. Howard, K.E. Money, and al. e.** Accuracy of aimed arm movements in changed gravity. *Aviat. Space Environ. Med.* 63:994-998, 1992.
25. **Boeing.** Statistical Summary of Commercial Jet Airplane Accidents in Worldwide Operations 1959-2006 Seattle, WA: Boeing Commercial Airplanes, 2007.
26. **Boff, K., J. and Lincoln.** Engineering data compendium: human perception and performance Wright-Patterson, A.F.B., Ohio: Harry G. Armstrong Aerospace Medical Research Laboratory, 1988.
27. **Borah, J., L.R. Young, and R.E. Curry.** Optimal estimator model for human spatial orientation IEEE Trans. Systems, 1979.
28. **Boyle, R., A.F. Mesinger, K. Yoshida, S. Usui, A. Intravaia, T. Tricas, and S.M. Highstein.** Neural readaptation to earth's gravity following return from space. *J. Neurosci.* 86:2118-2122, 2001.
29. **Braithwaite, M.G., K.G. Beal, E.A. Alvarez, H.D. Jones, and A. Estrada.** The optokinetic cervico reflex during simulated helicopter flight. *Aviat. Space Environ. Med.* 69:1166-1173, 1998.
30. **Burrough, B.** *Dragonfly: NASA and the Crisis Aboard Mir*. New York, NY: Harper-Collins, 1998.
31. **Campbell, M.R., D.R. Williams, J.C. Buckey, Jr., and A.W. Kirkpatrick.** Animal surgery during spaceflight on the Neurolab Shuttle mission. *Aviat. Space Environ. Med.* 76:589-593, 2005.
32. **Clark, J.B.** Neurologic issues related to landing performance. Houston, TX: NASA, 2002.
33. **Clark, J.B., and A.H. Rupert.** Spatial disorientation and dysfunction of orientation/equilibrium reflexes: aeromedical evaluation and considerations. *Aviat. Space Environ. Med.* 63:914-918, 1992.
34. **Clarke, A.H., J. Grigull, R. Mueller, H. and Scherer.** The three-dimensional vestibulo-ocular reflex during prolonged microgravity. *Exp. Brain Res.* 134:322-334, 2000.
35. **Clarke, A.H., W. Teiwes, and H. Scherer.** Vestibulo-oculomotor testing during the course of a spaceflight mission. *Clin .Investig.* 71:740-748., 1993.
36. **Clément, G., S.T. Moore, T. Raphan T, and B. Cohen.** Perception of tilt (somatogravic illusion) in response to sustained linear acceleration during space flight. *Exp. Brain Res.* 138:410-418, 2001.
37. **Clément, G.S.** *Fundamentals of Space Medicine*. El Segundo, CA: Microcosm Press, 2003, p. 102-105.
38. **Cohen, H.S., J. Wells, K.T. Kimball, and C. Owsley.** Driving disability and dizziness. *J Safety Res* 34: 361-369, 2003.
39. **Cooper, H.S.F.J.** *A House in Space*. New York, NY: Holt, Rhinehart & Winston, 1976.
40. **Currie, N.J., and B. Peacock.** International Space Station Robotic Systems Operations - A Human Factors Perspective. In: *Human Factors and Ergonomics Society Annual Meeting*. Baltimore, MD: HFES, 2001.
41. **Curry, I.P., and J.S. McGhee.** Spatial disorientation as a cause of accidents in combat helicopter operations. *Aviat. Space Environ. Med.* 2007.
42. **Curry, R.E., L.R. Young, W.C. Hoffman, and D.L. Kugel.** A pilot model with visual and motion cues. In:

Proc 12th Annual Conference on Manual Control, 1976.

43. **Demer, J.L., and F. Amjadi.** Dynamic visual acuity of normal subjects during vertical optotype and head motion. *Invest. Ophthalmol Vis. Sci.* 34:1894-1906, 1993.
44. **DiZio, P., and J.R. Lackner.** The effects of gravitoinertial force level and head movements on post-rotational nystagmus and illusory after-rotation. *Exp. Brain Res.* 70:485-495, 1988.
45. **Droulez, J., and C. Darlot.** The geometric and dynamic implications of the coherence constraints in three-dimensional sensorimotor interactions. In: *Attention and Performance XIII: Motor Representation and Control*, edited by Jeannerod M. Hillsdale, NJ: Lawrence Erlbaum Assoc., 1990, p. 495-526.
46. **Durnford, S.J., J.S. Crowley, N.R. Rosado, J. Harper, and S. DeRoche.** Spatial Disorientation: A survey of US army helicopter accidents 1987-1992 1995.
47. **Einstein, A.** Über das Relativitätsprinzip und die aus demselben gezogenen Folgerungen. *Jahrb Radioakt* 4:411-462, 1908.
48. **Ellis, S.R.** Collision in space: human factors elements of the Mir-Progress 234 collision. *Ergonomics in Design* 8:4-9, 2000.
49. **Endsley, M.** Toward a theory of situation awareness in dynamic systems. *Human factors* 37:32-64, 1995.
50. **Fernandez, C., and J.M. Goldberg.** Physiology of peripheral neurons innervating otolith organs of the squirrel monkey. III. Response dynamics. *J. Neurophys.* 39: 996-1008, 1976.
51. **Fernandez, C., J.M. Goldberg, and W.K. Abend.** Response to static tilts of peripheral neurons innervating otolith organs of the squirrel monkey. *J. Neurophys.* 35:978-987, 1972.
52. **Gazenko, O.G., A.M. Gernin, and A.D. Egorov.** *Major Medical Results of the Salyut-6 Soyuz 18 5day Space Flight*. 1981.
53. **Gillingham, K.K., and F.H. Previc.** Spatial orientation in flight. In: *Fundamentals of Aerospace Medicine*, edited by DeHart R. Baltimore, MD.: Williams and Wilkins, 1996, p. 309-397.
54. **Gillingham, K.K., and J.W. Wolfe.** Spatial orientation in flight. In: *Fundamentals of Aerospace Med.*, edited by DeHart R. Philadelphia, PA: Lea and Febiger, 1986, p. 299-381.
55. **Ginsberg, A.P., and J.M. Vanderploeg.** Vision in space: near vision acuity and contrast sensitivity. In: edited by M.W. Bungo, T.M. Bagian, M.A. Bowman and B.M. Levitan, Houston: NASA, 1987.
56. **Golding, J.F., W. Bles, J.E. Bos, T. Haynes, and M.A. Gresty.** Motion sickness and tilts of the inertial force environment: active suspension systems vs. active passengers. *Aviat. Space Environ. Med.* 74:220-227, 2003.
57. **Graybiel, A., E.F. Miller, and J.L. Homick.** Experiment M131. Human vestibular function. In: *Biomedical Results from Skylab*, edited by Johnston RS, and Dietlein LF. Washington, D.C.: NASA, 1977, p.74-103.
58. **Green, A.M., and D.E. Angelaki.** An integrative neural network for detecting inertial motion and head orientation. *J. Neurophys.* 92: 905-925, 2004.
59. **Griffin, M.J.** *Handbook of Human Vibration*. San Diego: Academic Press Inc., 1990.
60. **Grigoriev, A.I., S.A. Bugrov, V.V. Bogomolov, A.D. Egorov, I.B. Kozlovskaya, I.D. Pestov, V.V. Polyakov, and I.K. Tarasov.** Preliminary medical results of the Mir year-long mission. *Acta Astronautica* 23: 1-8, 1991.
61. **Grigoryan, G.A., O.G. Gazenko, I.B. Kozlovskaya, V.A. Barmin, and Y.V. Kreidich.** The Vestibulo-Cerebellar Regulation of Oculomotor Reactions in Microgravitational Conditions. In: *Adaptive Processes in Visual and Oculomotor Systems*, edited by Keller EL, and Zee DS. New York: Pergamon Press, 1986, p.111-120.
62. **Groen, J.J.** The semicircular canal system of the organs of equilibrium. *Physics Med. Biol.* 1: 225-242, 1957.
63. **Guedry, F.E.** Psychophysics of vestibular sensation. In: *Handbook of Sensory Physiology*, edited by Kornhuber HH. Berlin: Springer Verlag, 1974, p.3-154.
64. **Guedry, F.E., Jr.** Visual control of habituation to complex vestibular stimulation in man. *Acta Otolaryngol (Stockh)* 58:377-389, 1964.
65. **Guedry, F.E., A.R. Rupert, and M.F. Reschke.** Motion sickness and development of synergy within the spatial orientation system. A hypothetical unifying concept. *Brain Res. Bull.* 47:475-480, 1998.
66. **Gurfinkel, V.S., F. Lestienne, S. Levik Yu, K.E. Popov, and L. Lefort.** Egocentric references and human spatial orientation in mocrogravity II. Body-centered coordinates in the task of drawing ellipses with prescribed orientation. *Exp. Brain Res.* 95:343-348, 1993.
67. **Hanes, D.A. and G. McCollum.** Cognitive-vestibular interactions: a review of patient difficulties and possible mechanisms. *J. Vestib. Res.* 95:343-348, 2006.
68. **Harm, D.L., and D.E. Parker.** Perceived self-orientation and self-motion in microgravity, after landing and during preflight adaptation training. *J. Vestib. Res.* 3:297-305, 1993.
69. **Harm, D.L., M.F. Reschke, D.E. and Parker.** Visual-vestibular integration motion perception reporting (DSO 604 OI-1). In: *Extended Duration Orbiter Project Final Report 1989-1995*, edited by Sawin CF, Taylor GR, and Smith WL. Houston, TX: NASA Johnson Space Center, 1999, p.5.2-1 - 5.2-12.
70. **Harris, L., R. Dyde, C.M. Oman, M. and Jenkin.** Visual cues to the direction of the floor (abstract). In: *7th Symposium on the Role of the Vestibular Organs in Space Exploration*. European Space Technology Centre (ESTEC), Noordwijk, the Netherlands: European Space Agency, 2006.
71. **Herdman, S.J.** *Vestibular Rehabilitation*. Philadelphia: F. A. Davis Company, 1994.

72. **Hillman, E.J., J.J. Bloomberg, P.V. McDonald, and H.S. Cohen.** Dynamic visual acuity while walking in normals and labyrinthine-deficient patients. *J. Vestib. Res.* 9:49-57, 1999.
73. **Holmes, S.R., A. Bunting, D.L. Brown, K.L. Hiatt, M.G. Braithwaite, and M.J. Harrigan.** Survey of spatial disorientation in military pilots and navigators. *Aviat. Space Environ. Med.* 74:957-965, 2003.
74. **Holstein, G.R., and G.P. Martinelli.** The effect of space flight on the ultrastructure of the cerebellum. In: *The Neurolab Spacelab Mission Neuroscience Research in Space*, edited by Buckley JC and Homick JL. Houston: NASA, 2003.
75. **Homick, J.L., and M.F. Reschke.** Postural equilibrium following exposure to weightless space flight. *Acta Otolaryngol* 83:45 45-64., 1977.
76. **Howard, I.P., and G. Hu.** Visually Induced Reorientation Illusions. *Perception* 30:583-600, 2001.
77. **Hu, S., K.A. McChesney, K.A. Player, A.M. Bahl, J.B . Buchanan, and J.E. Scozzafava.** Systematic investigation of physiological correlates of motion sickness induced by viewing an optokinetic rotating drum. *Aviat. Space Environ. Med.* 70:759-765, 1999.
78. **Jacob, R.G., and J.M. Furman.** Psychiatric consequences of vestibular dysfunction. *Curr. Opin. Neurol.* 14:41-46, 2001.
79. **Jacob, R.G., J.M. Furman, J.D. Durrant, and S.M. Turner.** Panic, agoraphobia, and vestibular dysfunction. *Am. J. Psychiatry* 153:503-512, 1996.
80. **Jenkin, H.L., J.E. Zacher, M.R. Jenkin, C.M. Oman, and L.R. Harris.** Effect of field of view on the Levitation Illusion. *J. Vestib. Res.* 2007, submitted.
81. **Johnson, R.S., L.F. Dietlein, and C.A. Berry.** *Biomedical Results of Apollo*. Washington, D.C.: NASA, 1975.
82. **Jones, E.M.** Apollo Lunar Surface Journal http://www.history.nasa.gov/alsj/frame.html.
83. **Jones, T.D.** *Sky Walking: An Astronaut's Memoir*. New York, NY: Harper-Collins, 2006.
84. **Kanas, N., and D. Manzey.** *Space Psychology and Psychiatry*. El Segundo, CA: Microcosm Press, 2003.
85. **King, W.M., W. Zhou, B. Tang, and S. Newlands.** Neural processing of otolith signals in macaque vestibular nuclei [abstract]. In: *Vestibular Influences on Spatial Orientation A Satellite of the Society for the Neural Control of Movement, Ninth Annual Meeting*. Princeville, Hawaii, 1999.
86. **Knierim, J.J., B.L. McNaughton, and G.R. Poe.** Three-dimensional spatial selectivity of hippocampal neurons during space flight. *Nature Neurosci.* 3:209-210, 2000.
87. **Kornilova, L.N., A.M. Goncharenko, Korsunskii SB, Tarasov IK, and Alekseev VN.** Vestibular function and interanalyzer interaction following space flight. *Kosmiches. Biol. Aviakosmiches. Med.* 25:12-17, 1991.
88. **Kozlovskaya, I.B., V.A. Barmin, Y. Kreidich, and A.A. Repin.** The effects of real and simulated microgravity on vestibulo-oculomotor interaction. *Physiologist* 28:S51-56, 1985.
89. **Krasnov, I.B.** Gravitational neuromorphology. *Adv. Space Biol. Med.* 4:85-110, 1994.
90. **Kubis, J., E. McLaughlin, J. Jackson, D. Rusnak, G. McBride, and S. Saxon.** Task and work performance on Skylab missions 2, 3, and 4: Time and motion study - experiment M151. In: *Biomedical Results from Skylab*, edited by Johnston RS, Dietlein LF, and Berry CA. Washington DC: NASA, 1977, p.136-154.
91. **Lathan, C.E., and M. Tracey.** The effects of operator spatial perception and sensory feedback on human-robot teleoperation performance. *Presence: Teleop. Virtual Environs.* 11:368-377, 2002.
92. **Lee, M.H., S.J. Durnford, J.S. Crowley, and A.H. Rupert.** Visual vestibular interaction in the dynamic visual acuity test during voluntary head rotation. *Aviat. Space Environ. Med.* 68:111-117, 1997.
93. **Linenger, J.M.** *Off the Planet: Surviving Five Perilous Months Aboard the Space Station Mir*. New York, NY: McGraw-Hill, 2000.
94. **Lipshits, M.I., E.V. Gurfinkel, F. Matsakis, and F. Lestienne.** Microgravity effects on sensorimotor interaction during operational activity: visual feedback. Latent period of motor response. *Aerospace Environ. Med.* 27:22-25, 1993.
95. **Liu, E.** Ed Lu's Journal Entry #8 Which way is up? 2005.
96. **Lyons, T.J., W.R. Ercoline, J.E. Freeman, and K.K. Gillingham.** Classification problems of U.S. Air Force spatial disorientation accidents, 1989-91. *Aviat. Space Environ. Med.* 65:147-152, 1994.
97. **MacDougall, H.G., and S.T. Moore.** Functional assessment of head-eye coordination during vehicle operation. *Optom. Vis. Sci.* 82:706-715, 2005.
98. **Malcik, V.** Performance decrement in a flight simulator due to galvanic stimulation of the vestibular organ and its validity for success in flight training. *Aerospace Med.* 39: 941-943, 1968.
99. **Manzey, D., B. Lorenz, and V.V. Polyakov.** Mental performance in extreme environments: Results from a performance monitoring study during a 438-day spaceflight. *Ergonomics* 41:537-559, 1998.
100. **Manzey, D., B. Lorenz, A. Schiewe, G. Finell, and G. Thiele.** Dual-task performance in space: results from a single-case study during a short-term space mission. *Human factors* 37:667-681, 1995.
101. **Mayne, R.** A systems concept of the vestibular organs. In: *Handbook of Sensory Physiology*, edited by Kornhuber HH. Berlin Heidelberg New York: Springer Verlag, 1974, p.493-580.

102. **McCluskey, R., J. Clark, and P. Stepaniak.** Correlation of Space Shuttle landing performance with cardiovascular and neurovestibular dysfunction resulting from space flight. In: *Human Systems 2001*. Clear Lake City, TX, 2001.
103. **McDonald, P.V., J.J. Bloomberg, and C.S. Layne.** A review of adaptive change in musculoskeletal impedance during space flight and associated implications for postflight head movement control. *J. Vestib. Res.* 7:239-250, 1997.
104. **McRuer, D.T.** The development of pilot-in-the-loop analysis. *J. Aircraft* 10:515-524, 1972.
105. **Meddick, R.D.L., and M.J. Griffin.** The effect of two-axis vibration on the legibility of reading material. *Ergonomics* 19:21-33, 1976.
106. **Menchaca-Brandan, M.A., A.M. Liu, C. Oman, and A. Natapoff.** Influence of perspective-taking and mental rotation abilities in space teleoperation. In: *ACM/IEEE International Conference on Human-Robot Interaction*. Washington, D.C., 2007.
107. **Merfeld, D.M.** Effect of spaceflight on ability to sense and control roll tilt: human neurovestibular studies on SLS-2. *J. Appl. Physiol.* 81:50-57, 1996.
108. **Merfeld, D.M.** Rotation otolith tilt-translation reinterpretation (ROTTR) hypothesis: a new hypothesis to explain neurovestibular spaceflight adaptation. *J. Vestib. Res.* 13: 309-320, 2003.
109. **Merfeld, D.M.** Vestibulo-ocular reflex of the squirrel monkey during eccentric rotation with centripetal acceleration along the naso-occipital axis. *Brain Res. Bull.* 40:303-309, 1996.
110. **Merfeld, D.M., K.A. Polutchko, and K. Schultz.** Perceptual responses to linear acceleration after spaceflight: human neurovestibular studies on SLS-2. *J. Appl. Physiol.* 81:58-68, 1996.
111. **Merfeld, D.M., L.R. Young, C.M. Oman, and M.J. Shelhamer.** A multidimensional model of the effect of gravity on the spatial orientation of the monkey. *J. Vestib. Res.* 3:141-161, 1993.
112. **Merfeld, D.M., and L.H. Zupan.** Neural processing of gravitoinertial cues in humans. III. Modeling tilt and translation responses. *J. Neurophys.* 87:819-833, 2002.
113. **Mindell, D.A.** Digital Apollo: Human, Machine and Space Flight. Cambridge, MA: MIT Press, 2008.
114. **Mittelstaedt, H.** The role of the otoliths in perception of the vertical and in path integration. *Ann. NY Acad. Sci.* 871:334-344, 1999.
115. **Mittelstaedt, H.** The subjective vertical as a function of visual and extraretinal cues. *Acta Psycholog.* 63:63-85, 1986.
116. **Mittelstaedt, M.L., and H. Mittelstaedt.** The influence of otoliths and somatic graviceptors on angular velocity estimation. *J. Vestib. Res.* 6:355-366, 1996.
117. Moore ST, Clément G, Raphan T, and Cohen B. Ocular counterrolling induced by centrifugation during orbital space flight. *Exp. Brain Res.* 137:323-335, 2001.
118. **Moore, S.T., H.G. MacDougall, X. Lescue, J.J. Speyer, F. Wuyts, and J.B. Clark.** Head-eye coordination during simulated orbiter landings. *Aviat. Space Environ. Med.* 79:888-898, 2008.
119. **Moseley, M.J., and M.J. Griffin.** Effects of display vibration and whole-body vibration on visual performance. *Ergonomics* 29:977-983, 1986.
120. **Nicogossian, A.W., C. Leach-Huntoon, and S.L. Pool.** *Space Physiology and Medicine*. Philadelphia: Lea & Febiger, 1989.
121. **Oman, C.M.** A heuristic mathematical model for the dynamics of sensory conflict and motion sickness. *Acta Otolaryngol.* 392:1-44, 1982.
122. **Oman, C.M.** Human Visual Orientation in Weightlessness. In: *Levels of Perception*, edited by Jenkin LHaM. New York, NY: Springer Verlag, 2003, p.375-398.
123. **Oman, C.M.** Spatial Orientation and Navigation in Microgravity. In: *Spatial Processing in Navigation, Imagery and Perception*, edited by Janeke FW. New York: Springer Verlag, 2007.
124. **Oman, C.M., and M.D. Balkwill.** Horizontal angular VOR, nystagmus dumping, and sensation duration in Spacelab SLS-1 crewmembers. *J. Vestib. Res.* 3:315-330, 1993.
125. **Oman, C.M., D. Benveniste, D.A. Buckland, H. Aoki, A. Liu, and A. Natapoff.** Spacecraft module visual verticals and training affect spatial task performance. *Habitation* 10:202-203, 2006.
126. **Oman, C.M., and M.J. Kulbaski.** Spaceflight affects the 1-g post-rotatory vestibulo-ocular reflex. *Adv. Oto Rhino Laryngol.* 42:5-8, 1988.
127. **Oman, C.M., B.K. Lichtenberg, and K.E. Money.** Space motion sickness monitoring experiment: Spacelab 1. In: Crampton GH, *Motion and Space Sickness.* Boca Raton, FL: CRC Press pp.217-246, 1990.
128. **Oman, C.M., B.K. Lichtenberg, K.E. Money, and R.K. McCoy.** M.I.T./Canadian vestibular experiments on the Spacelab-1 mission: 4. Space motion sickness: symptoms, stimuli, and predictability. *Exp. Brain Res.* 64:316-334, 1986.
129. **Oman, C.M., E.N. Marcus, and I.S. Curthoys.** The influence of semicircular canal morphology on endolymph flow dynamics. An anatomically descriptive mathematical model. *Acta Otolaryngol.* 103:1-13, 1987.
130. **Oman, C.M., C.F. Pouliot, and A. Natapoff.** Horizontal angular VOR changes in orbital and parabolic flight: human neurovestibular studies on SLS-2. *J. Appl. Physiol.* 81:69-81, 1996.

131. **Page, N.G., and M.A. Gresty.** Motorist's vestibular disorientation syndrome. *J. Neurol. Neurosurg Psychiatry* 48:729-735, 1985.
132. **Paige, G.D., G.R. Barnes, L. Telford, and S.H. Seidman.** Influence of sensorimotor context on the linear vestibulo-ocular reflex. *Ann. NY Acad. Sci.* 781:322-331, 1996.
133. **Paige, G.D., and S.H. Seidman.** Characteristics of the VOR in response to linear acceleration. *Ann. NY Acad. Sci.* 871:123-135, 1999.
134. **Paloski, W.H., F.O. Black, M.F. Reschke, D.S. Calkins, and C. Shupert.** Vestibular ataxia following shuttle flights: effects of microgravity on otolith-mediated sensorimotor control of posture. *Am. J. Otology* 14:9-17, 1993.
135. **Panait, L., R.C. Merrell, A. Rafiq, S. Dudrick, and T. Broderick.** Virtual reality laparoscopic skill assessment in microgravity. *J. Surg. Res.* 136:198-203, 2006.
136. **Papaxanthis, C., T. Pozzo, K.E. Popov, and J. McIntyre.** Hand trajectories of vertical arm movements in one-G and zero-G environments. *Exp. Brain Res.* 120:496-502, 1998.
137. **Park, S., C. Gianna-Poulin, F.O. Black, S. Wood, and D.M. Merfeld.** Roll rotation cues influence roll tilt perception assayed using a somatosensory technique. *J. Neurophys.* 96:486-491, 2006.
138. **Parker, D.E., M.F. Reschke, A.P. Arrott, J.L. Homick, and B.K. Lichtenberg.** Otolith tilt-translation reinterpretation following prolonged weightlessness: implications for preflight training. *Aviat. Space Environ. Med.* 56:601-606, 1985.
139. **Peters, B.T., A.P. Mulavara, R. Brady, C.A. Miller, J.T. Richards, L.E. Warren, H.S. Cohen, and J.J. Bloomberg.** The use of dynamic visual acuity as a functional test of gaze stabilization following space flight. In: *The 7th symposium on the role of the vestibular organs in space exploration*. Noordwijk, The Netherlands: 2006.
140. **Peterson, B.W., and C. Chen-Huang.** Otolith neurons distinguish between translations and tilts. *J. Vestib. Res.* 11:255, 2002.
141. **Pompeiano, O.** Gene expression in the rat brain during space flight. In: *The Neurolab Space Mission Neuroscience Research in Space*, edited by Buckley JC Homick JL. Houston: NASA, 2003.
142. **Pozzo, T., A. Berthoz, L. and Lefort.** Head stabilization during various locomotor tasks in humans. I. Normal subjects. *Exp. Brain Res.* 82:97-106, 1990.
143. **Previc, F.H., W.R and Ercoline.** Spatial disorientation in aviation. In: *Progress in Aeronautics and Astronautics*. Reston, VA: AIAA, 2004.
144. **Previc, F.H., D.W. Yauch, C.A. DeVilbiss, W.R. Ercoline, and W.E. Sipes.** In defense of traditional views of spatial disorientation and loss of situation awareness. *Aviat. Space Environ. Med.* 66:1103-1106, 1995.
145. **Rafiq, A., R. Hummel, V. Lavrentyev, W. Derry, D. Williams, and R.C. Merrell.** Microgravity effects on fine motor skills: tying surgical knots during parabolic flight. *Aviat. Space Environ. Med.* 77:852-856, 2006.
146. Ramachandran VS. Perceiving shape from shading. *Sci. Am.* 259:76-83, 1988.
147. **Raphan, T., V. Matsuo, and B. Cohen.** Velocity storage in the vestibulo-ocular reflex arc (VOR). *Exp. Brain Res.* 35:229-248, 1979.
148. **Reason, J.T.** Motion sickness adaptation: a neural mismatch model. *J. Roy. Soc. Med.* 71:819-829, 1978.
149. **Reschke, M.F., J.J. Bloomberg, D.L. Harm, W.P. Huebner, J.M. Krnavek, W.H. Paloski, and A. Berthoz.** Visual-vestibular integration as a function of adaptation to space flight and return to Earth. In: *Extended Duration Orbiter Medical Project Final Report 1989-1995*, edited by Sawin CF, Taylor GR, and Smith WL. Houston: NASA, 1999, p.5.3-1-5.3-41.
150. **Reschke, M., J.M. Krnavek, J.T. Somers, and G. Ford.** *A Brief History Of Space Flight With A Comprehensive Compendium Of Vestibular And Sensorimotor Research Conducted Across The Various Flight Programs*. Houston: NASA, 2007.
151. **Reschke, M.F.** Microgravity vestibular investigations: Experiments on vestibular and sensory-motor adaptation to space flight. In: *Basic and applied aspects of vestibular function*, edited by Hwang JC, Daunton NG, and Wilson VJ. Hong Kong: Hong Kong University Press, 1988, p.205-217.
152. **Reschke, M.F., D.J. Anderson, and J.L. Homick.** Vestibulo-spinal response modification as determined with the H-reflex during the Spacelab-1 flight. *Exp. Brain Res.* 64:367-379, 1986.
153. **Reschke, M.F., D.L. Harm, D.E. Parker, G.R. Sandoz, J.L. Homick, and J.M. Vanderploeg.** Neurophysiologic aspects: space motion sickness. In: *Space Physiology and Medicine*, edited by Nicogossian AE, Huntoon CL, and Pool SL. Philadelphia: Lea & Febiger, 1994, p.228-260.
154. **Reschke, M.F., L.N. Kornilova, D.L. Harm, J.J. Bloomberg, and W.H. Paloski.** Neurosensory and sensory-motor function. In: *Space Biology and Medicine*, edited by Leach Huntoon CS, Antipov VV, and Grigoriev AI1996, p.135-193.
155. **Reschke, M.F., and D.E. Parker.** Effects of prolonged weightlessness on self-motion perception and eye movements evoked by roll and pitch. *Aviat. Space Environ. Med.* 58:A153-158, 1987.
156. **Robinson, D.A.** The use of control systems analysis in the neurophysiology of eye movements. *Ann. Rev. Neurosci.* 4:463-503, 1981.

157. **Rogers, W.F.** *Apollo Experience Report-Lunar Module Landing Gear Subsystem*. Houston: NASA, 1972.
158. **Ross, M.D.** A spaceflight study of synaptic plasticity in adult rat vestibular maculas. *Acta Otolaryngol.* 516:1-14, 1994.
159. **Ross, M.D.** Changes in ribbon synapses and rough endoplasmic reticulum of rat utricular hair cells in weightlessness. *Acta Otolaryngol* 120:490-499, 2000.
160. **Ross, M.D.** Morphological changes in rat vestibular system following weightlessness. *J. Vestib. Res.* 3: 241-251, 1993.
161. **Ross, M.D., and J. Varelas.** Ribbon synaptic plasticity in gravity sensors of rats flown on neurolab. In: *The Neurolab Space Mission: Neuroscience Research in Space*, edited by Buckley JC and Homick JL. Houston: NASA, 2003.
162. **Sangals, J., H. Heuer, D. Manzey, and al. e.** Changed visuomotor transformations during and after prolonged microgravity. *Exp. Brain Res.* 129:378-390, 1999.
163. **Schubert, M.C., S.J. Herdman, and al. e.** Vertical dynamic visual acuity in normal subjects and patients with vestibular hypofunction. *Otol Neurotol* 23:372-377, 2002.
164. **Schubert, M.C., S.J. Herdman SJ, and et al.** Functional measure of gaze stability in patients with vestibular hypofunction. *Ann. NY Acad. Sci.* 942:490-491, 2001.
165. **Shirley, R.S., and L.R. Young.** Motion cues in man-vehicle control. *IEEE Trans Mach Sys* 9:121-128, 1968.
166. **Sirota, M.G., B.M. Babayev, I.B. Beloozerova, A.N. Nyrova, S.B. Yakushin, I.B. and Kozlovskaya.** Characteristics of vestibular reactions to canal and otolith stimulation at an early stage of exposure to microgravity. *Physiologist* 30:S82-84, 1987.
167. **Smith, J.W., and J.W. Edwards.** *Design of a nonlinear adaptive filter for suppression of Shuttle Pilot-Induced Oscillation tendencies*. DFRC, 1980.
168. **Task, H.L., and L.V. Genco.** Effects of short-term flight on several visual functions. In: edited by M.W, Bungo, T.M. Bagian, M.A. Bowman and B.M. Levitan, Houston: NASA, 1987.
169. **Taube, J.S., R.W. Stackman, J.L. Calton, and C.M. Oman.** Rat head direction cell responses in zero-gravity parabolic flight. *J. Neurophys.* 92:2887-2997, 2004.
170. **Thornton, W.E., W.P. Biggers, W.G. Thomas, S.L. Pool, and N.E. Thagard.** Electronystagmography and audio potentials in space flight. *Laryngoscope* 95:924-932, 1985.
171. **Thornton, W.E., T.P. Moore, J. Uri, S.L. and Pool.** *Studies of the Vestibulo-Ocular Reflex on STS 4, 5, And 6*. Houston: NASA, 1988.
172. **Thornton, W.E., and J. Rummel.** Muscular deconditioning and its prevention in space flight. In: *Biomedical Results of Skylab,* edited by Johnston RS and Dietlein LF, Washington DC: NASA, 1977, p.191-197.
173. **Thornton, W.E., J.J. Uri, T. Moore, S. and Pool.** Studies of the horizontal vestibulo-ocular reflex in spaceflight. *Arch. Otolaryngol. Head Neck Surg.* 115:943-949, 1989.
174. **Tian, J.R., I. Shubayev, and J.L. Demer.** Dynamic visual acuity during transient and sinusoidal yaw rotation in normal and unilaterally vestibulopathic humans. *Exp. Brain Res.* 137:12-25, 2001.
175. **Uri, J.J., B.J. Linder, and T.D. Moore.** *Saccadic eye movements during space flight*. Houston: NASA, 1989.
176. **Vieville, T., and G. Clément.** Adaptive modifications of the optokinetic vestibulo-ocular reflexes in microgravity. In: *Adaptive Processes in Visual and Oculomotor Systems*, edited by Zee DS. New York, NY: Pergamon Press, 1986, p.111-120.
177. **Vogel, H., and J.R. Kass.** European vestibular experiments on the Spacelab-1 mission: 7. Ocular counterrolling measurements pre- and post-flight. *Exp. Brain Res.* 64:284-290, 1986.
178. **von Holst, E., and H. Mittelstaedt.** The reafference principle (interaction between the central nervous system and the periphery). In: *The Behavioural Physiology of Animals and Man*, edited by Martin R. Coral Gables: Univ. of Miami Press, 1973, p.139-173.
179. **Watt, D.G.** The vestibulo-ocular reflex and its possible roles in space motion sickness. *Aviat. Space Environ. Med.* 58:A170-174, 1987.
180. **Watt, D.G., K.E. Money, R.L. Bondar, R.B. Thirsk, M. Garneau, and P. Scully-Power.** Canadian medical experiments on Shuttle flight 41-G. *Can Aeronaut Space J.* 31:215-226, 1985.
181. **Watt, D.G.D.** Pointing at memorized targets during prolonged microgravity. *Aviat. Space Environ. Med.* 68:99-103, 1997.
182. **Welch, R.B.** Adaptation of space perception. In: *Handbook of Perception and Human Performance*, edited by Boff KR, Kaufman L, and Thomas JP. New York: John Wiley & Sons, 1986, p.24-145.
183. **Wertheim, A.H., B.S. Mesland, and W. Bles.** Cognitive suppression of tilt sensations during linear horizontal self-motion in the dark. *Perception* 30:733-741, 2001.
184. **Wiener, S.I., and J.S. Taube.** *Head Direction Cells and the Neural Mechanisms of Spatial Orientation.* Cambridge, MA: MIT Press Bradford Books, 2005.
185. **Williamson, P.** Mobile Servicing Systems Lessons Learned. In: *DX23 ISS Mechanical and Robotics Systems Training.* Houston, TX: NASA JSC 2007, p.7.
186. **Wood, S.J.** Human otolith-ocular reflexes during off-vertical axis rotation: Effect of frequency on tilt-translation ambiguity and motion sickness. *Neurosci. Letters* 323:41-44, 2002.

187. **Xerri, C., J. Barthelemy, F. Harlay, L. Borel, and M. Lacour.** Neuronal coding of linear motion in the vestibular nuclei of the alert cat. I. Response characteristics to vertical otolith stimulation. *Exp. Brain Res.* 65:569-581, 1987.

188. **Young, L.R.** On adaptive manual control. *Ergonomics* 12:635-674, 1969.

189. **Young, L.R.** Perceptions of the body in space: mechanisms. In: *Handbook of Physiology - The Nervous System,* edited by Darian-Smith I. Bethesda, MD: American Physiological Society, 1974, p.1023-1066.

190. **Young, L.R.** Some effects of motion cues on manual tracking. *J. Spacecraft* 4:1300-1303, 1967.

191. **Young, L.R.** Spatial Orientation. In: *Principles and Practice of Aviation Psychology,* edited by Vidulich PTaM. Mahwah, N.J.: Earlbaum, 2003, p.69-144.

192. **Young, L.R., J. Dichgans, R. Murphy, and T. Brandt.** Interaction of optokinetic and vestibular stimuli in motion perception. *Acta Otolaryngol.* 76:24-31, 1973.

193. **Young, L.R., and C.M. Oman.** Model for vestibular adaptation to horizontal rotation. *Aerospace Med.* 40:1076-1080, 1969.

194. **Young, L.R., C.M. Oman, D.G. Watt, K.E. Money, and B.K. Lichtenberg.** Spatial orientation in weightlessness and readaptation to earth's gravity. *Science* 225: 205-208, 1984.

195. **Young, L.R., and P. Sinha.** Spaceflight influences on ocular counterrolling and other neurovestibular reactions. *Otolaryngol. Head Neck Surg.* 118:S31-34., 1998.

196. **Young, L.R., B.L. Zuber, and L. Stark.** Visual and control aspects of saccadic eye movements. NASA CR-564. NASA Contractor Report, 1967.

197. **Zupan, L.H., R.J. Peterka, and D.M. Merfeld.** Neural processing of gravito-inertial cues in humans. I. Influence of the semicircular canals following post-rotatory tilt. *J. Neurophys.* 84:2001-2015, 2000.