Evidence Report

# Risk of Impaired Control of Spacecraft/Associated Systems and Decreased Mobility
# Due to Vestibular/Sensorimotor Alterations Associated with Space flight

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## Human Research Program
## Human Health & Countermeasures

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**TABLE OF CONTENTS**

## I. RISK TITLE: RISK OF IMPAIRED CONTROL OF SPACECRAFT/ASSOCIATED SYSTEMS AND DECREASED MOBILITY DUE TO VESTIBULAR/SENSORIMOTOR ALTERATIONS ASSOCIATED WITH SPACE FLIGHT

The National Aeronautics and Space Administration's (NASA) 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 Control of Spacecraft/Associated Systems and Decreased Mobility Due to Vestibular/Sensorimotor Alterations Associated with Space flight***. This risk is described as follows: *"Given that there is an alteration in vestibular/sensorimotor function during and immediately following gravitational transitions manifested as changes in eye-head-hand control, postural and/or locomotor ability, gaze function, and perception, there is a possibility that crew will experience impaired control of the spacecraft during landing or decreased mobility following a landing on a planetary surface (Earth or other) after long-duration space flight. These changes have not specifically been correlated with real time performance decrements. The risk of impairment is greatest during and soon after G-transitions when performance decrements may have high operational impact (landing, immediate egress following landing). The possible alterations in sensorimotor performance are of interest for Mars missions due to the prolonged microgravity exposure during transit followed by landing tasks. This risk must be better defined and documented and vestibular/sensorimotor changes must be correlated with performance issues."*

## II. EXECUTIVE SUMMARY

We examine the various dimensions of the ***Risk of Impaired Control of Spacecraft/Associated Systems and Decreased Mobility Due to Vestibular/Sensorimotor Alterations Associated with Space flight*** by reviewing the research and operational evidence demonstrating sensorimotor performance decrements during and after space flight. These sensorimotor performance decrements might affect vehicle and complex system control, including decreased visual acuity, eye-hand coordination, spatial and geographic orientation perception, and cognitive function. Sensorimotor performance decrements might also affect the ability to egress and walk away from the vehicle in case of an emergency or an extravehicular activity on a planetary surface. We also review the countermeasures that have been tested, including medication, prevention techniques and training exercises, physical rehabilitation, and mechanical devices. Furthermore, we identify the current knowledge and mitigation 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 sensorimotor changes on mobility and 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 (Shelhamer 2015).

## III. INTRODUCTION

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, posture, 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 (Paloski *et al.* 2008).

Thus, our current understanding of the ***Risk of Impaired Control of Spacecraft/Associated Systems and Decreased Mobility Due to Vestibular/Sensorimotor Alterations Associated with Space flight*** is limited primarily to extrapolation of scientific research findings, and, since there are limited ground-based analogs of the sensorimotor and vestibular changes associated with space flight, observation of their functional impacts is limited to studies performed in the space flight environment. Fortunately, many sensorimotor and vestibular experiments have been performed during and/or after space flight missions since 1959 (Reschke *et al.* 2007).  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 sensorimotor control that might bear on the physiological subsystems underlying this high-level integrated function.

## IV. EVIDENCE

This section begins with a summary of evidence obtained from 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 sensorimotor 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 obtained from space flight scientific investigations are provided in separate sections for in-flight and post-flight evidence. 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 offsetting 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.

### 1.1. Crew Verbal Reports

A number of (unpublished) crew verbal reports were obtained early after flight by some of the authors of this review. 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 hours) after flight. The first part of 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 post-flight symptoms varies widely among crewmembers, but both tend to decrease with increasing numbers of space flight missions. 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 International Space Station (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.

The second part of the discussion focus on the perceived ability of the crewmembers to egress the vehicle immediately after landing, in case they could not be assisted by the ground team due to an emergency. (PLT=pilot, MS=mission specialist, CMD=commander, PS=payload specialist) The crewmembers' response to Dr. Reschke's question: "**Could you have performed an emergency egress at wheels stop?"** are shown in italic*.*

**3908** (IIm‑PLT) *Yes. I don't really know how the disorientation would have affected me...coming down the ladder and getting out of the front seat there's a lot of turning. I think if I would have gone slow, I could have done it.*

**3227** (2s‑PLT) *No. It would have been difficult. I could have gotten out, but not in any hurry. No way.* [**What if you had to go out from the top***?]* I don't know if I could have made it. I could try.

**4171** (3s‑MS)Yes*.*

**3745** (13m-PLT) *Yes. It's a very personal thing. If I moved slowly and deliberately I could have gotten out. The fast motions cause you to crash over.*

**6064** (2m-PLT) *I'm not sure. It would have been a real workout. We had our strength, and we would have banged around, and we would have been slower, but it's a continuum, not yes or no, it depends.* **[What about though the hatch on top?]** *I think so, it would have been a real chore. Very, very demanding. Somebody ought to try it. And sooner than 40 minutes.*

**3029** (lm-MS) *No. Post-landing emergency egress is questionable. If you've got to get out in a hurry-- know I would have trouble. I tried to stand up, and immediately sat back down again. As I stood up, the lockers translated down, it didn't feel right. If I had to get out of the Orbiter during the first 5 or 10 minutes it would have been tough. It*

*wouldn't have been pretty. If I had to do anything that required any real coordination...* **[What about through the hatch on top?]** *Very difficult. No way. People are fooling themselves, the whole business of throwing a rope out and lowering down the side--no way. Some guys jump up and are ready to go. Some people more readily adapt.*

**5697** (16m-MS) *Yes.*

**2058** (SC) *No. I was unsteady, had ataxic gait, couldn't correct for my mistakes.*

**2042** (15m-CMD) *No. I think we would have major problems.* **[What about coming out of the top?]** *Impossible.*

**6855** (1s - MS) *No. I think there would be a pile of people in the hatch or at the bottom of the hatch. Vestibularly, it would worry me. Getting to the slide, I would have fallen at least once.*

**6245** (12s - MS) *Yes or No. I think if your life is threatened, you could run, but you're going to fall doing it. It would be one of these that you're going to get up and fall and get up and run. Sure, when there's a fire behind you, you're going to find your balance pretty fast.* **[What about going down the slide?]** *You would go flat on your face.*

**5157** (13s - CMD) *No. The pilot and commander would have a real problem getting out of their seat. We don't have anything to stand on. Can't stand up straight. Looked for help from Life Sciences--might be good to have something to pull myself out. The pilot and commander would have a hell of a time if it was life essential to get out.*

**8555** (4s - PS) *Yes or No. Depends on where you'd have to exit--out the hatch, ok. Out the top, it would be hard. Have to go slower.*

**4393** (14m-CMD) *Yes. It would have been slow, would not have been pretty. I would have tumbled down the chute, but I could have gotten out.* **[What about going down the slide?]** *It would have been tough, because of the suit.*

**6453** (4m - PLT) *Yes. Yeah, Yeah, Yeah I could have gotten out.* **[What about going down the slide?]** *Yeah.*

**5624** (3m - MS) *Yes. Yeah, hard to say, because if you were in an emergency, the adrenaline rush just sort of takes over. And it wasn't until I stopped being dizzy that I noticed I was really nauseated. So you tend to think, when you get done what you need to do and then your body has time to betray you.*

**5599** (12m - MS) *Yes or No. Probably couldn't have run, but I could have walked. Getting the slide out was my job. I could have done it not fast, but slow and methodically.*

## 1.2. Shuttle Entry and Landing Spatial Disorientation

A complete description of the space shuttle landing process, as well as plots of all shuttle landings touchdown point, sink rate, crossrange position, altitude, groundspeed, pitch attitude, and equivalent airspeed are given in Appendix A.

Despite 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, 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 were present during every Shuttle landing. At issue is whether the astronaut commander could successfully fly through the SD. Tilt-translation illusions and other sensorimotor disturbances (see below) did not occur in astronauts practicing approaches in the Shuttle Training Aircraft (STA), so their first actual experiences with these illusions occurred during their first actual return from space. Crews were forewarned about them, but they did not know how to predict the direction and magnitude of the effect, so a first-time flier did not know in advance which way to compensate. This was generally handled operationally by requiring commanders to have previous space flight experience (as pilots). Fortunately, for all Shuttle flights flown, there were no accidents specifically attributed to SD. However, several lines of circumstantial evidence suggest that the margin for error may have been less than generally recognized.
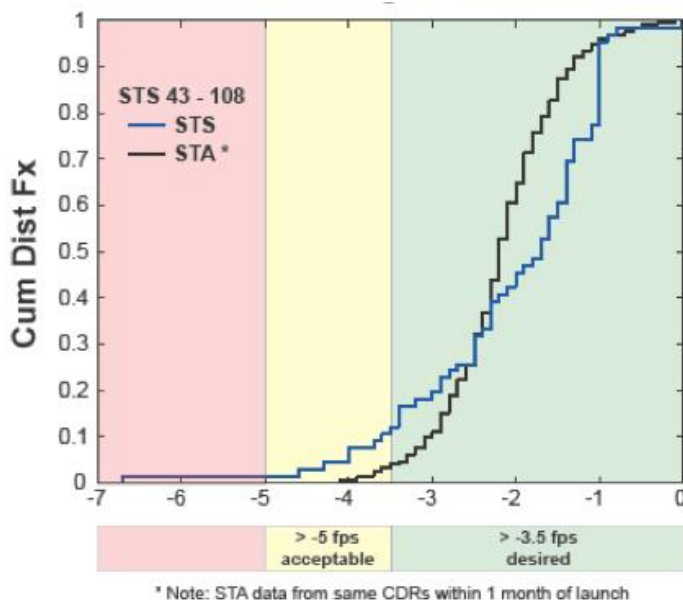


*Figure 1. Cumulative distribution functions allowing comparison between landing performances (vertical velocity at touchdown) before flight in the Shuttle Training Aircraft (STA) and those at the end of mission in the Space Shuttle (STS).*

All Shuttle landings were successful, but landing performance was more variable than desired. The timing and shape of the commander's control input during the flare depended 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 (Ashkenas *et al.* 1983). 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.* (2008a) 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). Clark (2002) also noted that the fastest landing on record (224 knots/hr) was linked to the commander's momentary spatial disorientation, 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. Figure 1 shows preflight performances flying the STA and subsequent post-flight 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 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 0.25 g deceleration of landing. However, it is possible that he under-perceived 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 were detected, adding a heads-up display (HUD) pitch attitude read-out, and restricting landings to low cross-wind and good visibility conditions probably prevented PIO recurrence. However, it is clear that control phase and gain margins during the landing maneuver were 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 examined returning Shuttle crewmembers for evidence of neurological dysfunction within several hours of landing. Crewmembers were scored for subjective symptoms, coordination, and functional motor performance. McCluskey *et al.* (2001) analyzed data from nine missions, and noted trends, such as a correlation between touch down sink rate and post-flight difficulty performing a sit-to-stand maneuver without using the arms. Scores indicating neurovestibular dysfunction generally correlated with poorer flying performances, including a lower approach and landing shorter, faster, and harder.

### 1.3. Apollo Lunar Landing Spatial Disorientation

A review of all Apollo lunar landings performance, visibility, and surface awareness is provided in Appendix B.

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. 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.

## 1.4. 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 (Ramachandran 1988) 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 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 (Rogers 1972). 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 (Jones & Glover 2014; Mindell 2008). 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 7° 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 land vehicles on Mars. 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.]

## 1.5. Rendezvous and Docking

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 sensorimotor 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 ms (Kolev & Reschke 2014). 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 sensorimotor problems (I.B. Kozlovskaya, personal communication). After the fact, Ellis (2000) performed a rigorous, quantitative analysis of the available visual and non-visual information and suggested a number of potential sensorimotor 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.

### 1.6. Teleoperator Tasks

The International Space Station (ISS) teleoperation system was heavily used during construction, and it will continue to be used to support extravehicular activities (EVA) operations, as well as in grappling/docking of rendezvousing cargo vehicles (Ruttley et al. 2010). Training and operating the Shuttle and ISS telerobotic manipulator systems as well as telerobotically controlled surface rovers presents significant sensorimotor challenges (Currie & Peacock 2001; Lathan & Tracey 2002; Menchaca-Brandan et al. 2007). 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 (Lathan & Tracey 2002; Menchaca-Brandan et al. 2007). 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 (Williamson 2007). A review of these incidents is given in Appendix C. 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.

### 1.7. Driving Performance

Driving a vehicle is one of the most complex sensorimotor/cognitive tasks attempted by most humans, and driving performance is known to be impaired in vestibular patients (Cohen et

*al.* 2003). Page & Gresty (1985) reported that vestibular patients experience difficulty in driving cars, primarily on open, featureless roads or when cresting hills, and MacDougall & Moore (2005a) reported that the vertical vestibulo-ocular reflex contributes significantly to maintaining dynamic visual acuity while driving. Adaptive changes in sensorimotor 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 (Mindell 2008) 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.

### 1.8. Implications for Exploration Class Vehicle Design

There are specific spatial disorientation issues to address with the exploration class vehicle (ECV) currently being designed for planetary exploration missions. As a capsule, this vehicle will differ from the Shuttle in opportunities to induce disorientation. In the ECV, crews will stow their seats after ascent, so there will be no up/down cues except for the cockpit panels and the windows. ECV, 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, Astronaut and member of Crew Exploration Vehicle 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.

### 1.9. Walking on the Moon

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. 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.

During the 6 Apollo missions on the Moon, 12 crewmembers performed 14 EVAs that lasted a total of 78 hours. During these 14 EVAs, there were 23 falls and 11 saves. The causes and consequences of these falls obtained from video analysis and from crew reports are indicated in Table 1.

| Mission | Falls | Saves | Lunar | EVAs | | Comments |
|---|---|---|---|---|---|---|
| Apollo 11 | 0 | 0 | 21.6 h | **1 EVA**<br>2 h 31 min | | * tendency to tip over on high jumps, but no problems overall |
| Apollo 12 | 2 | 0 | 31.5 h | EVA 1<br>4 h | EVA 2<br>3 h 50 | * never fell down flat, and were able to roll over and push themselves up |
| | | | | **TOTAL: 7 h 50 min** | | |
| Apollo 14 | 0 | 1 | 33.5 h | EVA 1<br>4 h 47 | EVA 2<br>4 hr 34 | * grabbed MESA before falling; no balance or stability problems overall<br>* one-sixth-g training helped them out |
| | | | | **TOTAL: 9 h 25 min** | | |
| Apollo 15 | 3 | 5 | 66.9 h | EVA 1<br>6 h 33 mins | EVA 2<br>7 h 12 min | * problems hopping down the ladder<br>* tripped on soft soil while taking pictures and also tripped on rocks<br>* worried about getting dirty to push themselves up<br>* possible fall dismounting Rover<br>* lost balance while throwing a used pallet<br>* not worried about suit popping or splitting even though fell down a couple of times; more concerned about rocks and unevenness<br>* fell climbing steep, soft rim of Station 6 crater<br>* potential for falling while down on one knee |
| | | | | **EVA 3**<br>4 h 50 min | | |
| | | | | **TOTAL: 18 h 30 min** | | |
| Apollo 16 | 10 | 4 | 71 h | EVA 1<br>7 h 11 | EVA 2<br>7 h 23 | * loss of balance at Rover seat tugging at Velcro<br>* problems retrieving objects from lunar surface (rock, bag, dust brush,penetrometer)<br>* stumbled and ran forward to keep from falling<br>* landed heavily on PLSS during jumping turn |
| | | | | **EVA 3**<br>5 h 40 min | | |
| | | | | **TOTAL: 20 h 14 min** | | |
| Apollo 17 | 8 | 1 | 75 h | EVA 1<br>7 h 12 | EVA 2<br>7 h 37 | * problems retrieving objects from lunar surface (tool and rock)<br>* fall with discus-like throw of bag<br>* problems removing deep core with jack<br>* fall getting on Rover and running across a slope |
| | | | | **EVA 3**<br>7 h 15 min | | |
| | | | | **TOTAL: 22 h 4 min** | | |

*Table 1. List of falls and close calls (saves) during the EVAs on the lunar surface.*

## 2. EVIDENCE OBTAINED FROM SCIENTIFIC INVESTIGATIONS IN FLIGHT

Both in-flight and post-flight sensorimotor responses are related to the length of time spent in a weightless environment (Lackner & DiZio 1993). During the flight, a number of acute and chronic sensorimotor events may occur, including: (a) space motion sickness; (b) spatial disorientation; (c) difficulty with acquiring and tracking visual targets; (d) vision changes due perhaps to reshaping of the eye; (e) modification of proprioception (e.g., pointing, knowledge of limb position); (f) modifications in vestibulo-spinal reflexes; and (g) loss of muscle tissue and motor efference (Lackner and DiZio, 2000). Some of these events may be due to changes in otoconial structure with associated modification of supporting neural tissue, as observed in animal studies.

Return to the Earth can also result in neurovestibular symptoms for some crewmembers. Limitations in performance can then be caused by: (a) post-flight motion sickness lasting from a few hours to more than a week; (b) hypo- or hypertonia of the major postural skeletal muscles which alter locomotion; (c) early muscle fatigability and potentiation of major postural muscle reflexes which lead to falls or other accidents; (d) frequent under- or overshooting when reaching for an object; (e) unilateral gaze nystagmus, which is associated with dizziness and vertigo; (f) saccadic intrusion during smooth pursuit tracking; and (g) postural ataxia, including an inability to perform a simple heel-to-toe tandem walk without falling.

The sections below review the evidence collected during on orbit and pre/post flight investigations.

## 2.1. Decrements in Sensation

### *2.1.1.  Visual Acuity*

Testing of Mercury, Gemini, and Apollo astronauts revealed few significant changes in visual function with the exception of the following: constriction of the visual field, changes in intraocular tension, and changes in the caliber of retinal vasculature. Some constriction of the visual field was noted post-flight as well as a decrease in unaided seven-meter visual acuity, although the latter was not statistically significant. Post-flight decrease in intraocular pressure was significant and returned to preflight levels more slowly than expected. Retinal photography revealed no lesions but did show a decreased size of retinal vessels (Clément & Reschke 2008; Clément 2011).

Anecdotal reports from early Shuttle crewmembers describing decreases in visual performance, such as difficulty in reading checklists and unstable focus in the cabin, led to additional ophthalmologic testing (Task & Genco 1987). In 1989, NASA incorporated a questionnaire into the post-flight eye examination, regarding subjective reports of in-flight visual changes during short- and long-duration space flight. Astronauts were queried as to whether they perceived a subjective improvement or degradation in distant or near vision. This post-flight survey of approximately 450 astronauts (including several who had one or more previous flights) documented that visual changes were commonly observed, particularly during long-duration space flight, with degradation in near vision being significantly more prevalent (Figure 2).

These near vision changes were noted to be hyperopic (farsighted) in nature and more clinically apparent in older astronauts with decreased lens accommodation (Ginsberg & Vanderploeg 1987). In response to documented anecdotal reports of changes in near vision during space flight, astronauts over the age of 40 are prescribed "Space Anticipation Glasses" in the event that they experience a hyperopic shift during the mission. This visual shift appears to occur gradually, is variable in magnitude, and may persist for years following return to Earth. The origin of the visual changes during space flight is thought to be posterior globe flattening and choroidal engorgement brought about by cephalad fluid shifts leading to a forward displacement of the retina. This shortening of the distance between the retina and the lens may account for the hyperopic shift in microgravity (Mader *et al*. 2011, 2013).
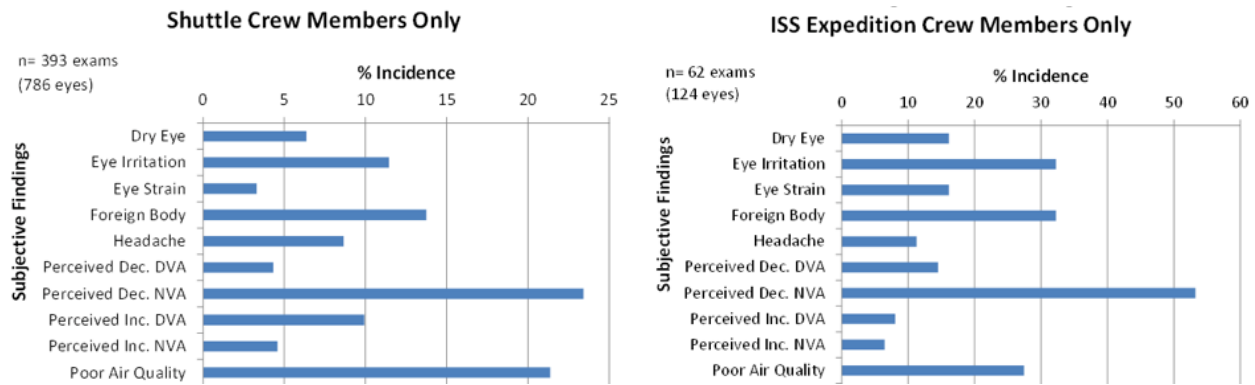
*Figure 2. Anecdotal ocular findings among Space Shuttle (left) and ISS crewmembers (right) from post-flight questionnaire. (DVA=distance visual acuity; NVA=near visual acuity; Dec=decrease; Inc=increase)*

### 2.1.2. Proprioception

Microgravity modifies the stimuli associated with proprioception and thus affects the astronauts' knowledge of position of their limb (Schmitt & Reid 1985; Reschke *et al.* 1986; Kornilova 1997). Altered proprioception has been observed to cause erroneous discrimination of mass while accelerating a ball up and down using whole-arm movements (Ross *et al.* 1984). Mass discrimination improves, however, with arm movements of higher acceleration, indication that the in-flight impairment is partly due to a reduction in the z-axis pressure stimulation that provides information about weight on Earth (Ross *et al.* 1986a, 1986b).

*T*wo theories exist to explain the observed decrements in proprioceptive function: (a) a physical degradation in the proprioceptive sensory system either via neural fiber degeneration, muscle atrophy, fluid shift, or the sudden and prolonged release of a constant muscle tone; (b) a disturbance of an external or internal-based spatial map. The results of pointing experiments suggest that gravity is important for the maintenance of a stable external spatial map (Young *et al.* 1993; Berger *et al.* 1997; Watt 1997). An egocentric reference system may also be used to assess limb position and maintain a sense of verticality (Kurtzer *et al.* 2005; Lackner & DiZio 2005b). This was observed aboard Mir when cosmonauts were able to draw ellipses in the air, either parallel or perpendicular to the longitudinal axis of the body, without visual aid. However, conflicting results have suggested there is a body scheme disturbance in the absence of gravity (Berger *et al.* 1992).

Proprioceptive illusions generated by vibrating leg muscles are different in-orbit compared to preflight. The perceptual effect of vibrating leg muscles was investigated in two subjects restrained on a back support. Before flight, leg vibration induced a backward and forward tilt sensation depending on which muscle was vibrated. After 20 to 21 days in orbit, the same vibrations caused a different whole body sensation. When the back support was used to replicate the axial force of normal gravity, the preflight illusions of forward and backward tilt returned (Roll *et al.* 1993). The results from a similar setup in parabolic flight demonstrated that

21

illusory movements were diminished in weightlessness but increased in hypergravity relative to 1 g. The authors concluded that the receptor output per unit stretch of a muscle spindle is influenced by variations in gravitational strength suggesting that unloading the otoliths in freefall decreases their descending modulation of alpha and beta motor neurons. This results in decreased tonic vibration reflexes (Lackner & DiZio 1992).

Proprioceptive illusions that involve self- or surround-motion have been observed for several muscle groups. The type and magnitude of illusion is influenced by the duration of space flight, the use of tactile cues, and whether the subject is restrained or free-floating. When crewmembers, wearing a special harness, were dropped from a quick-release hook, the sensation was one of the floor coming up rather than the subject falling. Most subjects reported that the floor suddenly slapped them on the feet (Reschke et al. 1984). The stretch reflex resulting from this landing propelled the subjects higher in the air than the height from which they were originally dropped.

However, there was a large variability in individual perception styles. Some subjects felt anchored by tactile cues from bungee cord-induced foot pressure, while others felt a tendency toward self-rotation under the same circumstances (Watt et al. 1992; Young et al. 1993). The CNS system that compares motor commands with sensory inputs may not be able to correctly distinguish between self-motion and movement of the environment because of sensory reinterpretation that occurs in space flight (Melvill-Jones 1974, Young et al. 1984; Parker et al. 1985; Reschke et al. 1986; Reschke & Parker 1987).

### 2.1.3. Motion Perception

Some cosmonauts have reported sensations of linear acceleration to occur after engine cut-off (Bryanov et al. 1986; Kornilova et al. 1983, 1995). The change in threshold for detecting linear acceleration during flight, during passive body motion using a sled or another crewmember, has been hard to determine (Arrott et al. 1986; 1990; Benson & Vieville 1986; Young et al. 1993). Considerable variability was seen across crewmembers between the in-flight and pre-flight responses. Threshold sensitivity does seem to be axis- and gravity- dependent, but the difference in unloading the saccular and utricular otolithic membranes has yet to be fully addressed (Clément & Reschke 1996).

During passive angular acceleration in orbit, perception of the angle of rotation was overestimated during both roll and pitch movements (Clément et al. 1987). Yaw was not affected because, much like on Earth, the otoliths do not play a large role in yaw stimulation (Armstrong et al. 2015). Using a multi-axis rotating chair to assess subjective response to passive angular motion in orbit, results showed that pitch motion resulted in a perceived tumbling sensation. One subject reported that roll rotation felt like yaw motion (Benson et al. 1986). Without a constant gravitational vector or visual cues, the subject's reference to the environment is established using intrinsic coordinates. If no sensory map is available to establish intrinsic coordinates, then the axis of rotation or orientation relative to extrinsic coordinates cannot be determined (Wright et al. 2006; Harm et al. 2015).

Rotating-dome experiments conducted during Spacelab missions showed that most subjects experienced increased intensity in their visually induced sensation of motion (called vection) in microgravity, with some reporting complete rotatory (saturated) vection during flight (Young *et al.* 1986; Young & Shelhamer 1990). The onset of linear vertical vection in free-floating cosmonauts was earlier than in ground-based tests. Subjects also reported the illusion of bending forward and pitch, rather than linear vection (Mueller *et al.* 1993). Visual-induced illusions become stronger in space, perhaps because the otolith organs neither confirm nor deny body tilt in microgravity.

## 2.2. Decrements in Gaze Control

Eye-head coordination 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 (Harm *et al.* 2007). A large body of evidence demonstrates that the G-transitions associated with space flight disrupt oculomotor performance. Highlights are summarized in the following subsections.

### 2.2.1. Smooth Pursuit Eye Movements

Smooth pursuit eye movements are produced during voluntary visual tracking of moving targets without head movements. Evidence suggests that the basic mechanisms underlying smooth pursuit tracking are modified by exposure to space flight. When crewmembers were asked to visually track a simple point stimulus at 0.33 Hz in either horizontal or vertical planes the amplitude of eye movement was reduced and the number of corrective saccades was increased (Kornilova *et al.* 1991a, 1991b; Reschke *et al.* 1999; Reschke *et al.* 1996). They crewmembers clearly undershot the target. The performance deterioration was the most pronounced for a point stimulus moving vertically or diagonally, early in-flight (flight day 3), late in flight (flight days 50, 116, and 164), and early after flight. Thus, it appears that 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 (Hopp & Fuchs 2006).

### 2.2.2. Vestibulo-Ocular Reflex

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. VOR function is plastic, meaning it can adapt to different environmental stimuli (Berthoz & Melvill Jones 1985). 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.*1996).

No significant changes in yaw VOR gain were observed in response to voluntary (active) head oscillations at frequencies ranging from 0.25 to 1 Hz (Thornton *et al.* 1985, 1988, 1989; Watt *et al.* 1985; Vieville & Clément 1986; Benson & Viéville 1986). 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 (Wood *et al.* 2009). 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, and the results are inconclusive. Some studies have reported no changes inflight (Watt *et al.* 1985) while others found an increase VOR gain and in the phase lag (delay between head motion and elicited eye motion) (Berthoz *et al.* 1986), and yet others reported a decrease in vertical VOR gain (Viéville *et al*. 1986; Clarke *et al.* 1993). Clarke *et al.* (2000) also reported changes in torsional VOR during voluntary head movements in the roll plane during and after space flight.

These findings suggest that VOR is presumably disrupted early after insertion into orbit. 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.

### 2.2.3. *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 (Kozlovskaya *et al.* 1985; Thornton *et al.* 1988; Tomilovskaya *et al.* 2011) and ocular saccadic performance (Uri *et al.* 1989; Andre-Deshays *et al.* 1993; Reschke *et al.* 1996, 1999).

Different strategies for gaze and target acquisition have been observed during and post-flight. Head movement towards a target near or beyond (≥ ±50°) the effective oculomotor (EOM) range is delayed, resulting in a VOR that tends to pull gaze off target (Reschke *et al.* 1999). Reduced angular positioning of the head forces larger compensatory eye saccades to direct the eye back to the target (Gresty & Leech 1977; Zangemeister & Stark 1981, 1982; Zangemeister *et al.* 1988, 1991) (Figure 3). The slower head movement contributes to a near doubling of the latency required to fixate peripheral targets. Sirota *et al*. (1987) 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.
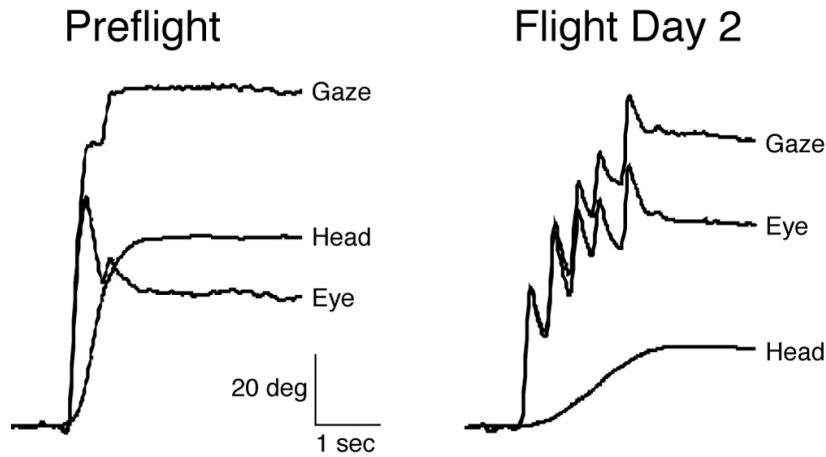


*Figure 3. Eye, head and gaze (sum of eye and head) position during target acquisition at the limits of the effective oculomotor range (50° in the horizontal plane). Note that on the second flight day the head rotation is delayed, the head moves at a much lower velocity than preflight, and the VOR is infused with several saccades to bring the eye on target.*

### 2.2.4. Optokinetic Nystagmus

Optokinetic eye movements that are produced in response to scene motion, whether it is induced by self-motion or surround-motion, offer a unique way to investigate the effects of space flight on the vestibular system, as the vestibular cells in the brainstem cannot themselves differentiate between visual scene movement and head movement relative to the environment. The asymmetry in optokinetic nystagmus (OKN) gain normally observed on Earth was reversed during the first 3 days of space flight and a downward drift was still evident on the fifth day, despite the gain and the eye movement field being nearly normal. A decrease in vertical OKN gain was also noted during flight, which increased shortly after flight, along with a restoration of asymmetry (Clément & Berthoz 1988, 1990). An experiment using short-radius centrifugation to elicit linear acceleration in orbit also indicated that the eye rotation axis during OKN tended to align with this linear acceleration (Moore *et al.* 2005a, 2005b). The reduced vertical asymmetry might reflect adaptation from a gravitational to an idiotropic reference frame in situations where vertical asymmetries have no functional use (Dai *et al.* 1994).

### 2.3. 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 (Bortolami *et al.* 2008). While not studied as intensively as oculomotor performance, a number of studies of eye-hand coordination have been performed during space flight missions.

### 2.3.1. Control of Aimed Arm Movements

When astronauts first encounter an altered gravity environment, arm movements are often inappropriate and inaccurate (Gazenko *et al.* 1981; Johnson *et al.* 1975; Nicogossian *et al.* 1989). During the Neurolab Space Shuttle mission (STS-90), Bock *et al.* (2003) 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 post-flight session, but no change in variability or timing compared with preflight values. In separate experiments, Watt *et al.* (1985, 1997) 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 (Berger *et al.* 1997; Papaxanthis *et al.* 1998), 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).

### 2.3.2. Reaching and Grasping

Thornton & Rummel (1977) showed that basic tasks such as reaching and grasping were significantly impaired during the Skylab missions. Later, Bock *et al.* (1996a, 1996b; Bock *et al.* 1992; Bock 1996; Bock & Cheung 1998; Hudson *et al.* 2005) 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.* (2003) 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.

### 2.3.3. 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.* (1993) found no differences in orientation or overall shape when crewmembers with eyes closed drew imagined ellipses oriented parallel or perpendicular to their long body axes. In another study, Lipshits *et al.* (1993) 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.* (1995, 1998) found that tracking errors were increased early in

flight, but gradually normalized within 2-3 weeks of exposure to the space environment. Step-tracking performance accuracy was also affected only marginally during flight in another experiment (Sangals et al. 1999). 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.

In another experiment where subjects tracked with their unseen finger a target moving along a circle at 0.5, 0.75, or 1.25 Hz, subjects' response paths were found to be elliptical rather than circular (Bock et al. 2003). The variability of finger positions about the best-fitting ellipse was significantly higher than preflight during the first in-flight session, and 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 post-flight 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. The investigators interpreted these observations as indicating an underestimation of mass during flight (Bock et al. 2003).

### 2.3.4. 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 (Lipshits et al. 1993; Reschke et al. 1996).

### 2.3.5. Fine Motor Control

Campbell et al. (2005) 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. (2006) 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. (2006) 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.

### 2.3.6.  Dual-Tasking and Manual Performance

Studies have demonstrated the effects of dual tasking on manual control during space flight. Manzey *et al.* (1998) found impairments in tracking performance and time-sharing efficiency during the first month in space. These impairments included larger single- versus dual-task differences of both memory search speed and tracking error in orbit compared to preflight. Bock *et al.* (2010) also found more tracking error for dual-task conditions inflight compared to preflight. Importantly, the increase in tracking error persisted for the duration of the mission and did not recover until four days after the return to Earth. Manzey *et al.* (1995) examined dual task performance for a crewmember throughout an 8-day space mission. Specifically, unstable tracking with concurrent memory search were tested 13 times during the course of the mission.  The results indicated impairments in the single task memory and dual task performance.  Based on the results from these studies, psychomotor processes and higher attentional functions are impaired when in the space environment.

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 (Kubis *et al.* 1977). 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.

## 2.4. Decrements in Spatial Orientation Perception

Spatial disorientation has been one of the most frequently studied aspects of sensorimotor adaptation during 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.

### 2.4.1.  Spatial Disorientation in Aviation

Spatial Disorientation (SD) is traditionally defined as a "failure to correctly perceive attitude, position, and motion of the aircraft" (Benson & Barnes 1978), as displayed on the aircraft's primary attitude and flight control displays. 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 Gillingham & Previc (1996), Young (2003), and Previc & Ercoline (2004). 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 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 (Gillingham & Wolfe 1986).

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 (National Transportation Safety Board [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 (Lyons *et al.* 1994; Holmes *et al.* 2003). 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 (Braithwaite *et al.* 1998; Durnford *et al.* 1995; Curry *et al.* 2007). Lack of reliable visual references has been the most frequent cause of helicopter SD fatalities, typically due to rain, fog, or 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 (Malcik 1968). However, applying such stimulation to pilots flying visual approaches can trigger pilot induced oscillations (MacDougall & Moore 2005a).

### 2.4.2. 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 (Antunano & Hernandez 1989). 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.

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 (GPWS), 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 (Boeing 2007). 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. terrain awareness and warning system [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 is defined as perception of elements defining a mental model of the current situation, comprehension of their meaning, and projection of their future status (Endsley 1995). Obviously, there are many dimensions to situation awareness, including all elements of spatial knowledge, as well as awareness of traffic, weather, autopilot mode, fuel, system, and weapon status, etc. The more general situation awareness 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 (Previc et al. 1995), but traditionally are not.

Overall, one concludes that large transport aircraft operations are relatively safe – less than one spatial disorientation related accident every 106 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.

### 2.4.3. Spatial Disorientation During Space Flight

The literature on spatial disorientation events during space flight has been well reviewed by Oman (2003, 2007). Numerous detailed firsthand accounts by astronauts and cosmonauts have also appeared (Cooper 1976; Burrough 1988; Linenger 2000; Lu 2003; Jones 2006; Hadfield 2013). 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 (what they call "the downs") that persists for 2 to 3 days after launch 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 (Mittelstaedt 1986a, 1986b, 1986c; Oman et al. 1986; Graybiel & Kellogg 1967).

On Earth, the ability to perceive verticality is quite good. This ability is dependent on input from visual, vestibular and somatosensory systems, and on a functioning CNS (Bortolami et al. 2006a, 2006b; Bryan et al. 2007). Many reports also exist of astronauts' perceptions of pitch-forward, pitch-up, or pitch-down attitudes once they enter weightlessness (Harm et al. 1994), giving rise to an altered subjective vertical. The perception of subjective visual vertical was

investigated in cosmonauts on short- and long-duration flights, either seated upright or rolled laterally (Bokhov *et al.* 1969; Bokhov *et al.* 1973; Kornilova & Kaspransky 1994). Immediately post-flight, all cosmonauts returning from long-duration flights and 38% of those returning from short-duration flights inaccurately perceived the subjective visual vertical. In the lateral position, the magnitude of error increased sharply and in the majority of cases altered attitude, relative to that observed preflight. In 10% of short-term and 18% of long-term mission cosmonauts, the previously occurring Aubert phenomenon gave way to the Müller phenomenon. The recovery of subjective vertical perception occurred 10-14 days post-flight. Interestingly, the accuracy of subjective perception of the body's vertical axis was virtually unchanged between pre- and post-flight testing.

Clément *et al.* (1987) examined in-flight adaptive changes in perception of subjective body orientation. They observed that when subjects' feet were held in Shuttle foot restraints, perception of subjective body orientation depended greatly on visual cues. Rotation around the ankle joint had little or no effect on correcting tilt angle in the absence of vision, which may be related to the lack of proprioceptive input during static limb positioning. The flexor tone produced in the dorsiflexor muscles has been proposed to help maintain a virtual vertical projection of the body's center of mass (Massion *et al.* 1997). In other words, the CNS tries to recreate a condition in weightlessness that is similar to that on Earth. This interpretation is in agreement with an internal representation of gravity (Mittelstaedt & Glasauer 1993; Clément *et al.* 2001), which allows a coherent mental representation of the body in alignment with the longitudinal axis. This internal model of gravity would also serve as a reference frame for movement.

### 2.4.4. Visual Reorientation Illusion

The visual reorientation illusion (VRI) has been first described by astronauts on the Skylab and Spacelab-1 missions. When crew float about in the cabin, they experience a spontaneous change in the subjective identity of surrounding surfaces, such that the "surface beneath my feet seems somehow like a floor." Oman (2003, 2007) 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 (Mittelstaedt & Mittelstaedt 1996). 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.

The type and magnitude of perceptual illusions may depend on whether a crewmember uses an idiotropic or visual reference frame. Individuals who are visually oriented with respect to external references perceive themselves to be inverted or sideways during flight. They report difficulty in switching rest frames and performing coordinate transformations, in addition to experiencing loss of orientation in the absence of visual cues. When an idiotropic reference

frame is used, the alignment of a vertical along the longitudinal body axis allows little disorientation and an easy switch between rest frames. Forty-six percent of astronauts and 58% of cosmonauts were classified as using an idiotropic reference frame, 46% of astronauts and 34% of cosmonauts as using predominantly visual reference, and 8% of both crews were classified as using a mixed of both (Young *et al.* 1986; Friederici & Levelt 1990; Harm & Parker 1993). Individual experiences with self- or surround-motion may vary, but commonly reported illusions include (a) exaggerated rate, amplitude, and positioning of body movement; (b) temporal disturbance to perception of motion; and (c) altered path perception (Harm *et al.* 1999).

Data from animal experiments in parabolic and orbital flight (Taube *et al.* 2004; Oman 2007) 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 section 2.4.6). 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 (Harm *et al.* 2008). For example, investigators have shown 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 (Hu *et al.* 1999; Howard & Hu 2001, Jenkin *et al.* 2007). Single planar surfaces or the longer surface in a rectangular room interior were most frequently identified as "down." (Oman 2007)  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 2007 and Aoki *et al.* (2006, 2007) have 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 (Oman 2006).

### 2.4.5. 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 (1908) was the first to postulate "the complete physical equivalence of a gravitational field and a

corresponding acceleration of the reference system." 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 (Mayne 1974; Merfeld *et al.* 2005a, 2005b). This hypothesis appears consistent in principal with the response dynamics of the different primary otolith afferents (Fernandez *et al.* 1972; Fernandez & Goldberg 1976; Peterson & Chen-Huang 2002), secondary processing of otolith input in the vestibular nuclei (Xerri *et al.* 1987; King *et al.* 1999), and also with natural behavior (Pozzo *et al.* 1990). 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 (Guedry 1974; Angelaki *et al.* 1999). 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 (Young 1974; Oman 1982; Droulez & Darlot 1990; Zupan *et al.* 2000; Green & Angelaki 2004; Poon & Merfeld 2005; Zupan & Merfeld 2005).

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 (Paige *et al.* 1996). 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 (1999) reported that the crossover frequency is approximately 0.5 Hz in primates, and Wood (2002) 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 sensorimotor adaptation, active voluntary motion may be one of the most important (Welch 1986). Performing visual tasks with the intent to override vestibular input may also catalyze adaptation (Guedry 1964; Shelhamer *et al.* 2010, 2012). Most sensory conflict theories related to sensorimotor adaptation have been derived from the concept of "efference copy", which states that there are predicted sensory feedbacks for any given motor action (Von Holst & Mittelstaedt 1973; Reason 1978). Head movement kinematics on Earth yield invariant unique patterns of canal and otolith signals irrespective of other sensors (Guedry *et al* 1998). 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 (Watt 1987) and post-flight postural and dysfunction (Bloomberg *et al.* 1997).


Two separate human experiments conducted on orbit by Reschke *et al.* (1988) and Clément *et al.* (2001) investigated the effects of sustained linear accelerations during eccentric rotation created by short-radius centrifuges. Interestingly, subjects report no sense of translation in either experiment during the constant velocity centrifugation. In orbit exposure to 0.2 Gz at the head during 60 s of constant velocity was insufficient to provide a vertical reference (Benson *et al.* 1997), possibly because of the opposing G-gradient along the trunk and legs and/or the relatively small resultant force level (Mittelstaedt 1999). When subjects were exposed to greater force levels (0.5 Gy and 1.0 Gz) for up to 5 min, these forces did provide a vertical reference on orbit. The subjects perceived roll-tilt when the resultant force was directed along the interaural axis, and inversion when the resultant force was directed towards the head (Clément *et al.* 2001). Ocular counterrolling was also unchanged during this experiment (Moore *et al.* 2001).

### 2.4.6. *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 (Wiener & Taube 2005), 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 (Knierim *et al.* 2000; Taube *et al.* 2004). 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.

### 2.5 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. Kanas & Manzey (2003) provide a good overview of the relevant evidence. As should be clear from the evidence presented here, 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 (Jacob & Furman 1996, 2001). Hanes & McCollum (2006) 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. In the following sections the results of space flight investigations on the mental representation of space (mental rotation, three-dimensional visual perception, distance perception) are reviewed.

### 2.5.1. Mental Rotation

The face of a well-known person is not as easily recognized when presented upside down. This phenomenon suggests that people have difficulty recognizing familiar shapes when they are in an unfamiliar orientation (Howard & Templeton 1966; Howard 1982; Finke & Shepard 1986; Cohen, 2000). In such circumstances, mental rotation is necessary for shape and facial recognition. Until crewmembers become adept at mentally rotating themselves and/or their environment, and/or develop new spatial maps, they can easily become disoriented. Poor ability to mentally rotate the visual environment could be an important factor in determining susceptibility to space motion sickness (Parker & Harm 1992).

Mental image rotation and reconstruction experiments were performed on orbit. During STS-51G, mental reconstruction after body tilt demonstrated that the critical angle was 65°, which is comparable to values attained on Earth (Corballis *et al.* 1978). After 3 days of microgravity, the subjects could mentally rotate the environment even while they were in an inverted position (Clément *et al.* 1987). The investigators proposed that mental rotation could be a gravity-dependent process and that weightlessness, by releasing this constraint, facilitates processing of visual images in any orientation. In contrast, Léone *et al.* (1995) suggested that mental rotation depends on symmetry detection and an internal vertical reference. In the absence of gravity, detection of symmetry was less accurate and required more time. The discrepancies between findings may be attributed to procedural differences, use of subject restraint, and difficulty of mentally manipulating test objects.

Experiments using mental rotation of three-dimensional objects (Shepard & Metzler 1971) in the yaw and roll axes, while subjects were restrained, showed that response times and error rates were similar before and during flight. These results were consistent with those of Friederici & Levelt (1987, 1990) and Léone *et al.* (1995), and support the conclusion that mental rotation of visually presented 3-D objects is independent of gravity.

### 2.5.2. Distance and Size Perception

Further space flight-related changes occur in cognitive visual-spatial processing, which helps in perception of distance and size of objects. Distance and size perception are skills learned through repetitive practice. Normally sighted, binocular and even totally monocular people develop and use effective distance and size perception skills (Beaton *et al.* 2015). Monocular depth cues include angular variations—or parallax—when moving the head; texture, luminosity, color, and shading variations of the visual scene; and perspective.

In microgravity, the environment is not structured with a gravitational reference and a visual horizon, so perspective is less relevant. Astronauts perceive heights and depths of objects as taller and shallower on orbit, respectively (Lathan *et al.* 2000; Clément *et al.* 2013), and there

are changes in the perception of geometric illusions and perspective-reversible figures after 3 months in space (Clément *et al.* 2012, 2015). These changes may occur because the perspective cues for depth are less salient in microgravity (Clément *et al.* 2015a). Ground-based studies also showed that the occurrence of geometric illusions based on perspective is reduced when subjects are tilted relative to the gravitational normal (Clément & Eckardt 2005) and in patients with vestibular deficits (Clément *et al.* 2009). Consequently, the changes in 3D visual perception in orbit reduction are presumably due to the altered peripheral otolith input or to a central adaptation in the processing of visuo-spatial cognitive function (Clément & Reschke 2008).

On Earth, horizontal distances relative to the observer are accurately estimated up to 4 m, and underestimated by approximately 10% as distance increases (Daum & Hecht 2009). By contrast, vertical distances are overestimated by about 30%, especially when looking down (Stefanucci & Profitt 2009). During a recent study, 6 astronauts were presented with stereoscopic (anaglyphs) photographs of natural scenes. Small yellow targets were superimposed on easily recognizable landmarks within each scene, e.g., a remarkable building, the end of a bridge, the top of a mountain, or the bottom of a tower. The subjects were asked to estimate the absolute distance between themselves and the target (egocentric distance) using a conventional metric of their choice (e.g., feet, yards, or meters). On average, the astronauts reported distances above 50 m to be about 20%-25% smaller in-flight than pre-flight (Figure 4). One interpretation for this underestimation of distance in flight is that the distance between the eyes and the floor varies when astronauts are free floating; therefore they cannot use the eye height scaling to estimate distance and size as on Earth (Clément *et al.* 2013).
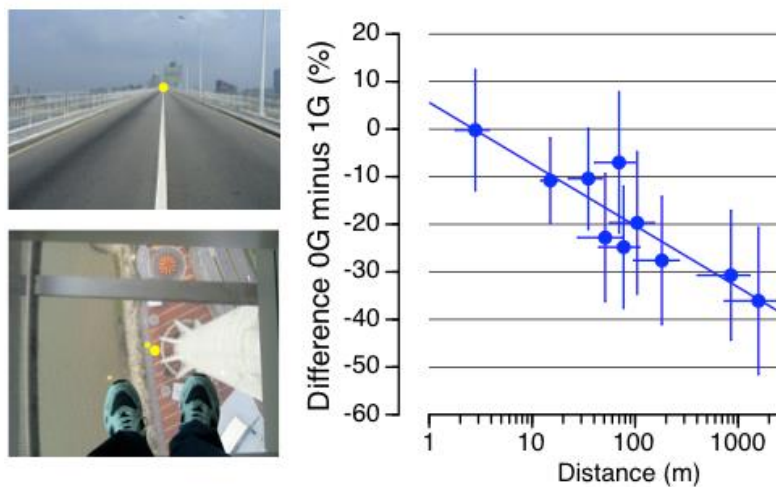


*Figure 4. Differences in egocentric distance estimations using natural scenes between inflight and preflight conditions (Clément et al. 2013).*

Distortions of the visual space during space missions may influence astronauts' ability to accurately perform cognitive and sensorimotor tasks, such as those involved in robotic operations. Additionally, this misperception will alter how astronauts view their habitat and workspace volume. These are important considerations for future human planetary exploration missions, and warrant further investigation and consideration for countermeasure development (Clément *et al.* 2013).

### 2.5.3. Time Perception

Some astronauts and cosmonauts have reported a "time compression syndrome" in orbit, whereby time is subjectively sensed as compressed relative to the perceptions gained during training and simulation (Schmitt & Reid 1985; Albery & Repperger 1992). Another perception experienced by the astronauts is that longer time than normal is required to execute standard mental activity (Manzey & Lorenz 1998). Yet another reported syndrome is "space fog", which affects cognitive performance during the first weeks of a mission (Welch *et al.* 2009).

Following the historical one-orbit flight of Gagarin, Titov flew on board Vostok-2 for a full day (17 Earth orbits), and performed the first cognitive neuroscience experiments in orbit. The objective of one experiment was to assess his ability to evaluate time intervals. After starting a stopwatch, he began to count 20 s in his mind; when he estimated subjectively that 20 s had passed, he stopped the stopwatch and looked at the actual elapsed time. The average time estimates during the 4 in-flight sessions were not significantly different from those measured during training, but they were biased by the fact that he had continuous feedbacks on his performance (Leonov & Lebedev 1968).

Another experiment on time perception in microgravity was performed on four astronauts during a 4-day Space Shuttle mission. Subjects viewed a visual target traversing a display and, while it was obscured, estimated the time of its arrival at a predetermined point by any means other than counting. The time perception for short duration tasks (2 s) were consistently overestimated in 0 g. As the time duration of the task increased, the subjects tended to underestimate. These errors in duration estimates increased each day as the flight progressed. Three hours after landing the duration estimates were also significantly larger than on flight day 4 (Ratino *et al.* 1988). These results suggest that the ability to estimate brief intervals of time deteriorate during a short space mission and after landing.

Similar effects were also observed in subjects exposed to hypergravity in a centrifuge (Albery & Repperger 1992). The authors point out that one potential consequence of these effects is that crewmembers who need to make quick decisions and perform critical tasks in-flight and re-entry may exhibit some delays in their responses, which would compromised safety. Clément *et al.* have proposed an experiment on board the International Space Station whose objective is to investigate whether the subjective perception of time is affected during and after long-duration space flight.

## 2.6. Space Motion Sickness

### 2.6.1. History

Space motion sickness (SMS) is the most clinically significant neurosensory phenomenon experienced by crewmembers during the first few days of space flight, and its effect may be almost as significant immediately after returning to Earth (Lackner and DiZio, 2006). The neurosensory and motor systems and their relationship with the vestibular system were extensively studied during the early Space Shuttle missions. The major focus during that time was the prevention of SMS, which is characterized by a plethora of symptoms, such as

somnolence, vomiting, stomach awareness, fatigue, and performance decrements. No correlation was found between SMS and terrestrial motion sickness in terms of crewmember susceptibility. As a result of these studies, many preflight sensorimotor tests were abandoned due to their misrepresentations of induced mechanisms during actual space flight. On the other hand, post-flight postural instability and ataxia were evaluated and studied in greater detail to better understand the prevention of injuries during locomotion or emergency egress immediately after landing.

### 2.6.2. Symptoms

On Earth, exposure to provocative motion, whether real or apparent, leads to the progressive cardinal symptoms of terrestrial motion sickness, which typically include the following: pallor, increased body warmth, cold sweating, dizziness, drowsiness, nausea, and vomiting. Although similar, the symptoms associated with SMS differ slightly from those of acute terrestrial motion sickness, probably because of differences in the physical environment, such as the lack of normal air-current vection and of gravitational force on the contents of the stomach. In particular, sweating, except for palmar sweating (Oman *et al.* 1990), is uncommon during space flight, and flushing is more common than pallor. SMS, as compared to acute terrestrial motion sickness, typically is more often associated with stomach awareness, vomiting, headache (due perhaps to headward fluid shifts), impaired concentration, lack of motivation, and drowsiness (Thornton *et al.* 1987a; Davis *et al.* 1988; Oman *et al.* 1990). Vomiting is usually sudden and infrequent, and is often not marked by prodromal nausea. Bowel sounds, obtained by auscultation, are decreased or absent in crewmembers experiencing SMS (Thornton *et al.* 1987b; Harris *et al.* 1997). Despite these differences, nearly universal symptoms are malaise, anorexia or loss of appetite, lack of initiative, and (for some) increased irritability.

### 2.6.3. Incidence

Historically, as the size of space vehicles has increased, so has the incidence of SMS. No SMS was reported in either Project Mercury or Project Gemini (Homick 1985), but 35% of the Apollo Program astronauts and 60% of the Skylab Program crewmembers developed symptoms of SMS (Davis *et al.* 1988). The incidence of SMS was 67% among first-time flyers on 24 Space Shuttle flights. Statistically, symptom occurrence was not different between career vs. non-career astronauts, commanders and pilots vs. mission specialists, men vs. women, different age groups, or first-time vs. repeat flyers. However, observations of U.S. astronauts suggest that the incidence of post-flight sickness may be higher in women than in men (R. Billica, personal communication, 1999). Current estimates are that 80% to 90% of all Shuttle crewmembers experienced some symptoms of motion sickness (R. Billica, personal communication, 1999). An astronaut's susceptibility to SMS on his or her first flight correctly predicted susceptibility on the second flight in 77% of the cases (Davis *et al.* 1988).

Russian researchers report that 54% of cosmonauts have symptoms lasting 1 to 3 days, 25% have symptoms lasting 14 days or longer, and 8 of 46 cosmonauts on long-duration missions (85-365 days) periodically developed vertigo and queasiness, especially during the last

10 to 14 days of the mission, when their activity increased (Bryanov *et al.* 1986; Kornilova *et al.* 1995).

No reports of post-flight motion sickness (PFMS) were noted in the Space Shuttle program through the mid-1980s (Thornton *et al.* 1987a). However, it now appears that this syndrome affects a similar percentage of both U.S. and Russian crews. The Russian reports indicate that PFMS symptoms generally occur in cosmonauts who have SMS in-flight. However, 11% of those who experience little or no SMS on orbit do experience mal de débarquement (Bryanov *et al.* 1986). Postflight medical debriefs were examined for Shuttle missions from the beginning of the program, in April 1981, through January 1999, which involved 241 crewmembers having flown between one and six missions. Postflight, 32% of crewmembers reported vertigo, 14.7% reported nausea, and 8% vomiting (Bacal *et al.* 2003).

PFMS onset occurs in a time pattern similar to that of SMS. Within minutes of g-force onset during re-entry symptoms may already be developing. Crewmembers who have no symptoms during re-entry and landing may develop symptoms as soon as they stand up to exit the vehicle. The severity of the symptoms and the functional recovery seem to be directly proportional to the time on orbit. There have been reports of a "relapse" phenomenon in the post-landing recovery course. Astronauts who are exposed to certain types of inertial environments, like turning a corner in a car or lying in bed in the dark, can bring on a sudden return to an early postflight state of maladaptation, which may elicit 'mild' to 'severe' PFMS symptoms several days up to a week after return to Earth. Recovery from this "relapse" generally occurs more rapidly than the recovery immediately after returning from orbit (Ortega & Harm 2008).

Like SMS, PFMS does not appear to correlate with gender, age, crew position, or number of previous flights (Reschke *et al.* 2014). Past experience with postflight re-adaptation does not seem to affect incidence (Bacal *et al.* 2003). PFMS is likely complicated by the relative dehydration upon return and orthostatic intolerance following flight.

### 2.6.4. *Provocative Stimuli*

Microgravity by itself does not induce space sickness. The larger a volume of spacecraft and the mobility of their inhabitants, the higher chance of SMS. Specifically, factors that may initiate or worsen SMS include distasteful, unpleasant, or uncomfortable sights, noxious odors, certain foods, excessive warmth, loss of 1-g orientation, and head or whole-body movements (Jennings 1998). Similarly, post-flight symptoms may be induced and/or exacerbated by warmth and head movements during reentry and immediately after landing. Hypersensitivity to angular head motions is also common; crew members have reported that head movements in the pitch plane are initially more provocative than those made in other planes (Thornton *et al*. 1987a; Oman *et al.* 1990).

### 2.6.5. *Theories and Hypotheses*

Many theories and hypotheses have been proposed to explain SMS. The *fluid shift* theory (Barrett & Lokhandwala 1981; Parker *et al*. 1983) postulates that headward fluid shifts accompanying weightlessness produce changes that alter the response properties of vestibular

receptors. However, this theory is not ideal in that it fails to adequately address the development of motion sickness during space flight.

The *sensory conflict* theory from Reason & Brand (1975) assumes that human orientation in three-dimensional space, under normal gravitational conditions, is based on at least four sensory inputs (otolith organs; semicircular canals; visual system; and touch, pressure, and somatosensory systems) to the CNS. Motion sickness may result when the environment is altered in such a way that information from sensory systems is not compatible and does not match previously stored neural patterns. It is important to note that it is the combination, rather than a single course, of these conflicts that somehow produces sickness, although the exact physiological mechanisms remain unknown.

In the *poison* theory, Treisman (1977) suggested that the purpose of mechanisms underlying motion sickness, from an evolutionary perspective, was not to produce vomiting in response to motion, but to remove poisons from the stomach. Money and colleagues (1970, 1996) concluded that the mechanism to facilitate vomiting in response to toxins is partly vestibular.

 The *otolith mass asymmetry* hypothesis describes a mechanism complementary to the sensory conflict theory that explains adaptation to weightlessness, readaptation to 1 g, and individual differences in susceptibility to SMS (von Baumgarten & Thuemler 1978; von Baumgarten *et al.* 1982; Kornilova *et al.* 1983). According to this theory, some individuals possess slight functional imbalances between right and left otolith receptors that are compensated for by the CNS in 1 g. *Sensory compensation* (Parker & Parker 1990) occurs when the input from one sensory system is attenuated and signals from others are augmented.

Finally, the *Otolith Tilt-Translation Reinterpretation (OTTR)* hypothesis assumes that because of the fundamental equivalence between linear acceleration and gravity, graviceptors signal both the head orientation with respect to gravity (tilt) and a linear acceleration of the head that is perceived as translation. As a consequence of the absence of sensed gravity during orbital flight, graviceptors do not respond to static pitch or roll in weightlessness; however, they do respond to linear acceleration. Because stimulation from gravity is absent during space flight, interpretation of the graviceptor signals as tilt is meaningless. Therefore, during adaption to weightlessness, the brain reinterprets all graviceptor output to indicate translation (Young *et al.* 1984; Parker *et al.* 1985). The *sensory compensation* and *OTTR* hypotheses have both been further refined by Merfeld (2003) and Clément & Reschke (2008).

### 2.6.6.  Predicting Susceptibility

The prediction of susceptibility to motion sickness has long been of interest to space flight researchers. Since most motion sickness treatments are more effective when they are administered before symptoms develop, the identification of individuals susceptible to SMS would allow preventive measures to be taken only by those requiring them, and would free insusceptible persons from the undesirable side effects of anti-motion sickness medications and/or the scheduling requirements of pre-training (Diamond & Markham 1991).

A number of predictors for motion sickness have been investigated and can be grouped into the following categories: exposure history, physiological predisposition, psychological predisposition, plasticity, provocative tests, and operational measures (Clément & Reschke 2008). The real test of any predictive method relies on the use of data from crewmembers. Ground-based measures on normative subjects, while useful, are not true measures of the criterion of interest, SMS. Until enough flight data become available, along with ground-based tests for flight personnel, the relationships between various predictors and SMS susceptibility will remain unclear.

## 2.7. Impacts of Vestibular Changes to Orthostatic Intolerance

The vestibular system is required for motion sickness to occur, but the exact neural pathways involved are still unknown. Understanding the role of the vestibular system in autonomic regulation is essential to understanding SMS (Davis et al. 1988, 1993). Some authors argue that unusual motion or direct vestibular stimulation triggers a poison response (Money et al. 1996). The poison response consists of a stress response and stomach emptying. Vomiting is primarily associated with increases in parasympathetic activity, whereas stress responses are primarily associated with increases in sympathetic activity or decreases in parasympathetic activity (or both). The most direct pathway for vestibular modulation of autonomic responses involved in motion sickness is efferent projections from the medial and inferior vestibular nuclei to the nucleus tractus solitarius (NTS) in the brainstem and the dorsal motor nucleus of the vagus. The NTS plays an integral role in both gastric motility and emesis related to motion sickness (Ito & Honjo 1990). The NTS receives input from peripheral and central ascending fibers (Onai et al. 1987; Barron & Chokroverty 1993), and in turn influences vagal stimulation of the stomach and heart and activation of the sympathetic nervous system (Yates 1992; Previc 1993; Yates et al. 1993; Yates & Miller 1996). The cerebellum may be another route through which vestibular inputs may modulate autonomic activity (Wood et al. 1994; Balaban 1996).

## 2.8. Peripheral and Central Neural Changes Associated with Space Flight

The radiation environment in exploration class missions poses a greater threat to the CNS than the environment for ISS astronauts since they are partially protected by the Earth. During a short-duration mission, astronauts may experience detrimental CNS changes in cognition, short-term memory, motor function, and behavior. Late responses to radiation damages can include premature aging, Alzheimer's disease, or other dementia (Cucinotta 2014). Radiation exposure in low Earth orbit is ultimately caused by galactic cosmic rays (GCR) and solar particle events (SPEs). Although all dose regimens have the potential to cause decrements in performance and cognition, it is the low to moderate levels (~ 1 to 2 Gy) of charged-particle exposure that will define the space radiation environment for crewmembers during long-duration space flights (Nelson 2009). In a study in which mice were exposed to 0.1 and 1 Gy of whole body proton irradiation, dendritic complexity was significantly dependent upon dose reduction, and the number and density of dendritic spines along hippocampal neurons of the dentate gyrus was significantly reduced (Parihar 2014).

Vertebrates sense gravitoinertial acceleration by mechanoreceptors in the otolith organs of the inner ear. These structures consist of ciliated sensory hair cells with crystals of calcium carbonate called otoconia placed on top of the hair cells that stimulate the hair cells when moved due to linear acceleration or tilt. Inner ear structures can regulate their function through adaptive processes by increasing or decreasing production of calcium carbonate in response to a sustained decrease or increase in the amplitude of gravity, altering otolith mass and subsequent transduction gain of the system. Boyle et al. (2015) used electron microscopic techniques to image otoconia mass obtained from (a) mice exposed to both 91-days of weightlessness in the ISS and 91-days of 2 g centrifugation on ground, and (b) mice flown on short-duration Shuttle missions. Results from ISS showed a clear restructuring of individual otoconia with increased deposition and mass while the 2 g counterparts showed a decrease in otoconial mass. Conversely, for shorter duration exposures to weightlessness (13-days) the otoconia appeared to be normal. Therefore, long-duration exposure to space flight may induce adaptive mechanisms that lead to structural alterations in peripheral end organ transduction of motion contributing to behavioral disturbances.

The brain may also undergo structural remodeling as a result of microgravity exposure, radiation exposure, and vascular changes associated with space flight (Carpenter et al. 2010). The brain's structural organization is not fixed but rather can undergo extensive remodeling, even in the adult brain. These changes occur in response to skill learning (Karni et al. 1995), recovery from brain insult such as stroke (Cramer et al. 1997), and as a result of cognitive training (Olesen et al. 2004). Moreover, brain plasticity occurs as a result of disuse such as prolonged bed rest (Roberts et al. 2010). Animal studies have shown that microgravity exposure results in structural brain changes. Research with rats has demonstrated that brain structural changes occur as a result of microgravity exposure, particularly in the somatosensory cortex (Krasnov 1994; Newberg 1994; D'Amelio et al. 1998) and cerebellum (Holstein 1999; Holstein & Martinelli 2003). These changes include decreased synapses and degeneration of axonal terminals. It has been has demonstrated that hair cells in the rat utricular macula undergo extensive plasticity as a result of space flight, with a large (40-55%) increase in synapse number (Ross 1993, 1994, 2000, 2003). This plasticity remained evident following the flights, even after posture control in the rats had returned to normal. Therefore, in humans potential structural changes associated with long-duration space flight could have behavioral implications for both space flight operations and long-term health of crewmembers. Studies are currently being conducted with ISS crewmembers that will identify potential changes in brain structure and function following long-duration space flight using magnetic resonance imaging techniques to assess the risks of changes in brain structure and the impact on sensorimotor and cognitive function (Erdeniz et al. 2013; Koppelmans et al. 2013).

## 3.  EVIDENCE OBTAINED FROM SCIENTIFIC INVESTIGATIONS DURING REENTRY AND AFTER LANDING

### 3.1. Decrements in Postural Equilibrium

The first studies, designed to quantify post-flight postural ataxia, required astronauts, upon landing, to tandemly stand on narrow rails of various widths with their eyes either open or closed and arms folded across their chests (Berry & Homick 1973; Homick & Miller 1975; Homick *et al.* 1977; Homick & Reschke 1977; Kenyon & Young 1986). Other studies have used static force plates for stabilometry and simpler tests, such as the clinical Romberg test, a sharpened (toe-to-heel) Romberg test, and vertical posture with varying head positions, to assess postural ataxia immediately after flight (Bryanov *et al.* 1976; Yegorov 1979; Clément *et al.* 1984). Other postural performance studies have relied on dynamic posture platforms that translate the subject (Reschke *et al.* 1984; Clément *et al.* 1985; Anderson *et al.* 1986), tilt the subject (Kenyon & Young 1986; Reschke *et al.* 1991), or provide more sophisticated means of posture control such as stabilization of ankle rotation and/or vision (Paloski *et al.* 1993). Pre- and post-flight studies of vestibulo-spinal reflexes (Baker *et al.* 1977; Reschke *et al.* 1984; Kozlovskaya *et al.* 1984; Watt *et al.* 1986) and postural responses to voluntary body movements (Clément *et al.* 1984; Reschke *et al*. 1988) have also been performed.

**Unstable Platform, Eyes Closed**

**Head Erect**

ISS Expeditions 1-29

**Tc 19hr (above) versus 111hr (below)**

**Dynamic Head Tilts**
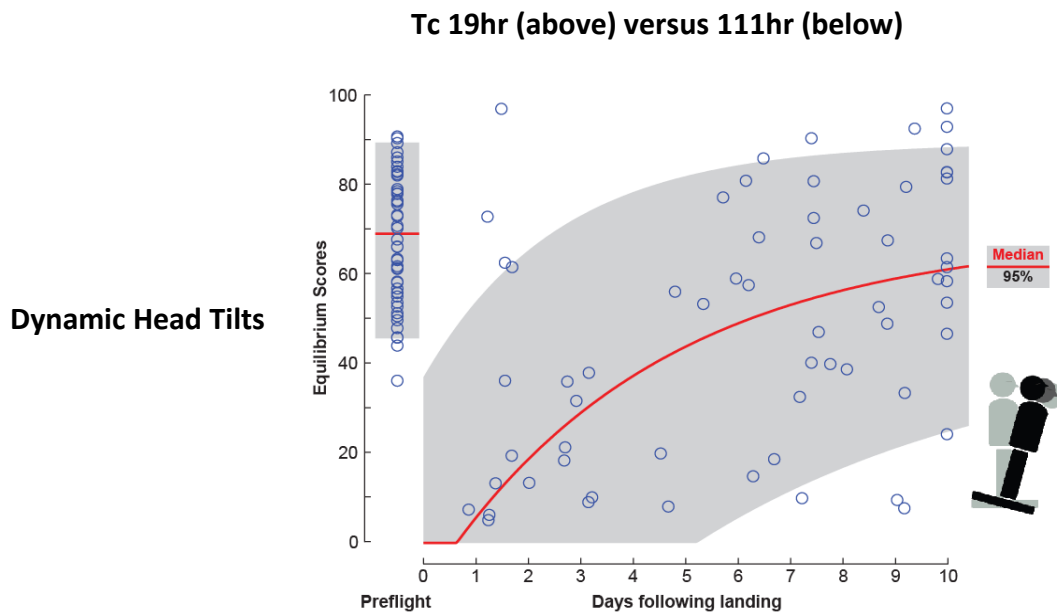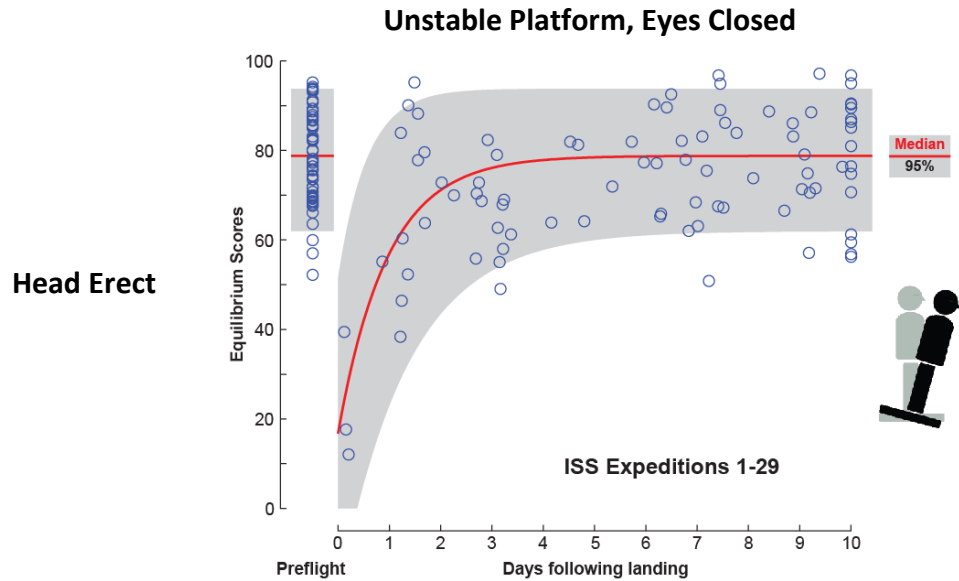
*Figure 5. Equilibrium (EQ) score during computerized dynamic posturography evaluation after ISS missions. High EQ score means more stability. Data points show responses for individual crewmembers preflight and postflight. The gray area represents the 90% confidence limit region around the median score (red line) for all crewmembers. Adapted from Wood et al. 2015.*

The greatest decrease in stability occurs when subjects must rely on vestibular information alone, when proprioceptive or visual feedback is either altered or absent. Decrements in postural stability with eyes closed are well documented from Skylab missions and were observed to persist for up to 1-2 weeks post-flight (Homick *et al.* 1977). Computerized dynamic posturography (CDP) evaluations conducted after ISS flights clearly demonstrated that postural

stability was diminished (Figure 5). Recovery of postural stability after landing occurs in two phases: initial rapid improvement followed by a gradual recovery. Both the initial decrement and the time required for recovery vary as a function of flight duration. Stability is further compromised during dynamic head tilts (0.33Hz @ ±20° in pitch plane), with a time constant of recovery of 19hr for head erect versus 111hr for head moving, so that the majority of crewmembers are unable to maintain quiet stance for 20 sec. The extent of the postural stability decrement may also reflect previous space flight experience (Clark & Bacal 2008). Paloski et al. (1990, 1993, 1994) reported that veteran astronauts seem to have better post-flight postural performance than first-time fliers. A more recent within-subject analysis of CDP data comparing performance decrements on a similar post-flight day suggests that ~60% of veteran astronauts were more stable following repeat flights (2010, not publicly available).

A few physiological factors are known to contribute to space flight-induced postural instability (Forth et al. 2011). Firstly, the dorsiflexor muscles play a larger role in space than the extensor muscles, which are used to counteract gravity on Earth (Clément et al. 1984). This causes astronauts to assume a forward tilted posture when asked to stand perpendicular to the spacecraft floor. A small flexor tone is generated in order to maintain the feet at a right angle to the leg, as this is the normal neutral posture of the ankle (Clément & Lestienne 1988). Another explanation for this posture in microgravity is that the normal excitatory drive exerted by input from the otoliths, by way of the vestibular nuclei, on the extensor muscles is inhibited due to the lack of gravity.

Changes in vestibulo-spinal reflexes may also contribute to postural decrements. The Hoffmann reflex and otolith-spinal reflexes were dramatically reduced during space, but differences between pre- and post-flight responses were not significant (Watt et al. 1986). Reschke et al. (1986) observed a potentiation of the Hoffman reflex 40 ms after astronauts underwent an unexpected drop (Earth-vertical fall with bungee cords) during flight; this potentiation disappeared after 7 more days. Immediately after space flight, there was significant potentiation again compared to preflight responses. Such changes in the Hoffman reflex are predictive of change in the gain of the spinal reflex pathway. How gain changes in this pathway are linked to preprogrammed muscular activity such as the maintenance of posture is not clear.

## 3.2. Decrements in Locomotion

### 3.2.1. Locomotor Control and Segmental Activation

Most crewmembers experience some degree of locomotor dysfunction when they return to Earth after space flight. Some of these post-flight alterations are ataxia with the sensation of turning while attempting to walk a straight path; sudden loss of postural stability when rounding corners or after unexpected perturbations; and sudden loss of orientation in unstructured visual environments. In addition, some astronauts report oscillopsia (illusory movement of the visual field) while walking.

Foot contact with the ground, the transfer of weight from one foot to the other, and the pushoff with the toe from the ground are critical phases, as these interactions with the support

surface result in forces that create vibrations, which if unattenuated could interfere with the visual-vestibular sensory systems in the head (Voloshin 1988; Smeathers 1989; Pozzo *et al.* 1990; Valiant 1990; Lafortune *et al.* 1996; Ito *et al.* 1997; McDonald *et al.* 1997; Whittle 1999; Mulavara *et al.* 2005a; Mulavara & Bloomberg 2003). The musculoskeletal system controls these vibrations; muscles and joints act as filters to minimize the perturbing effects of impacts with the ground and help to maintain a stable trajectory at the head (Holt *et al.* 1995, McDonald *et al.* 1997). During treadmill walking after returning from long-duration space flight, astronauts' knee flexion during the stance phase significantly increased, but it returned to normal within 6–10 days (Bloomberg & Mulavara 2003). An increase in knee flexion during locomotion will result in reduction of the axial stiffness of the lower-limb complex during the critical stance phase following heel strike, leading to reduced perturbations being transmitted to the head during locomotion.

Distinct post-flight performance decrements in gait have been observed in cosmonauts returning from Soyuz missions lasting 2 to 63 days (Chekirda *et al.* 1971; Bryanov *et al.* 1976; Chekirda & Yermin 1977). In most cases, the duration of post-flight effects correlated with the duration of the mission. Post-flight changes in locomotion included increased angular amplitude of motion at the knee and ankle, and increased vertical accelerations of the center of mass (Hernandez-Korwo *et al.* 1983).

Post-flight locomotor control and segmental coordination show alterations in muscle activation. Layne *et al.* (1997, 1998b) reported that the temporal relationship and relative amplitude of muscle activation are modified by space flight, particularly for the events of heel-strike and toe-off that are complementary to evidence of changes in kinematics during locomotion at these events of the gait cycle (McDonald *et al.*, 1996; Miller *et al.* 2010). The loss of neuromuscular coordination may cause difficulty in achieving optimal transitions between muscles while walking (Courtine *et al.* 2002). This loss in coordination between muscles may also affect the ability to maintain stable head movement (Layne *et al.* 2004, 2001) and are complimentary to evidence seen in alterations in head-trunk coordination during walking (Bloomberg and Mulavara, 2003; Bloomberg *et al.*, 1997; Mulavara *et al.*, 2012); reduced visual acuity during walking (Peters *et al.*, 2011) and impairment in the ability to coordinate effective landing strategies during jump tasks (Newman *et al.*, 1997; Courtine and Pozzo, 2004). Other neurophysiological changes including proprioceptive hyper-reactivity, such as increased Hoffman reflex amplitudes; reduced ability to perform graded muscle contractions; and decreased muscle stiffness (Grigoryeva & Kozlovskaya 1987) may also have a contributory influence on muscle coordination during locomotion activity.

Activation of ankle-joint muscles post-flight has been heavily investigated. Zangemeister *et al.* (1991) concluded that space flight-related adaptive modifications in neural processing of vestibular input could negatively influence activation of lower limbs. This change, in combination with altered strength between ankle plantar flexors and dorsiflexors (Hayes *et al.* 1992), can cause difficulty in walking.

Changes in ankle musculature activation are suggested to result in reinterpretation of proprioceptive input (Roll *et al.* 1993). Ankle proprioception is no longer interpreted as coding anterior-posterior body sway while upright, but instead codes either whole body axial transportation (i.e., pushing off the support surface) or foot movement exclusively. In addition, the extent of reinterpretation correlates with duration of mission. Despite being appropriate for weightlessness, these changes are maladaptive on return to Earth and may contribute to post-flight decrements in locomotion.

### 3.2.2. Head-Trunk Coordination

Gaze and head movement control stabilizes vertical and horizontal vision during various motor tasks such as jumping, walking, running, hopping and/or tasks requiring a person to maintain equilibrium on a beam or a moving platform (Assaiante *et al*. 1993; Pozzo *et al*. 1995). The head serves as a stable platform to provide a veridical reference frame for visual, vestibular, and proprioceptive integration, facilitating the organization of postural and locomotor control patterns (Pozzo *et al.* 1990; Bloomberg *et al.* 1992; Bloomberg and Mulavara 2003; Mulavara *et al.* 2002; Mulavara *et al.* 2003; MacDougall & Moore 2005b). Another system that benefits from head stabilization with respect to the environment is the system for maintaining gaze during body movement. Head movements actually contribute to gaze stabilization during locomotion (Bloomberg *et al.* 1992). An example of this is the pitch head rotation (as in nodding the head), which compensates for the vertical translation of the trunk that occurs with each step during the gait cycle. The magnitude of these head rotations was observed to be controlled as a function of the distance of the visual target to the eyes. The goal-directed nature of these head movements during concurrent locomotion and visual target fixation suggests that head movements are not completely dependent on passive inertial and viscoelastic properties of the head-neck system but are actively modulated to respond to altered gaze control requirements. Thus, head stabilization mechanisms help adjust posture, to maintain balance of the moving body, and maintain visual acuity for navigational control through a constantly varying environment during locomotion.

In an initial study, Bloomberg *et al*. (1997) examined whether short-duration exposure (7–16 days) to the microgravity environment of space flight during Shuttle missions induces alteration in post-flight head-trunk coordination during locomotion. Before space flight, pitch head movements acted in a compensatory fashion to oppose vertical trunk translation during locomotion. As the trunk translated upward, the head pitched forward and downward, assisting in maintaining target fixation. Following space flight, coordination between compensatory pitch angular head movements and vertical trunk translation was significantly altered. Like patients with vestibular deficits (Keshner 1994, 1995) and children prior to development of their mature head stabilization response (Assaiante *et al*. 1993), head movements were restricted during locomotion. This change in head-trunk coordination strategy may account, in part, for the reported oscillopsia that occurs during post-flight locomotion and may contribute to disruption in descending control of locomotor function. Comparison of responses from multi- and first-time astronauts indicated that astronauts who had experienced more than one space flight demonstrated less post-flight alteration in the frequency spectra of pitch head movements than subjects on their first flights.

Changes in head-trunk coordination during locomotion were also characterized in returning Mir crewmembers (Bloomberg & Mulavara 2003). These subjects walked (6.4 km/h) on a treadmill before and after space flight while visually fixating on an earth-fixed target. At this walking speed, head pitch movements compensate for the vertical trunk movements that occur during each step (Pozzo *et al*. 1990, 1995; Bloomberg *et al*. 1997). Subjects showed a reduction in head movements in the frequency range of 1.5-2.5 Hz reflecting the contributions of reflexive head stabilization mechanisms (Keshner *et al.* 1995) during post-flight locomotion followed by a recovery trend spanning several days. This reduction in head pitch movement occurred despite no significant change in trunk pitch or vertical movement. Therefore, during post-flight locomotion head movement amplitude with respect to space was reduced.

Bloomberg *et al.* (1997), Davids *et al.* (2003), Mulavara *et al.* (2005a) and Madansingh and Bloomberg (2015) have shown that tasks requiring sensorimotor integration after an adaptive exposure are associated with a wide range of adaptive behavioral responses. Specifically, after short-duration space flight, astronauts showed diverse responses, with some showing increases and others showing decreases in the magnitude of head pitch movement during walking (Bloomberg *et al.* 1997). A report from Mulavara *et al.* (2012) confirms and extends this observation of response variability one day after return from long-duration space flight on board the ISS. Subjects were classified into two groups according to the pre- and post-flight averages of the magnitude of their head pitch movements during locomotion: a "decreaser" group wherein subjects' post-flight average head pitch movements decreased with respect to their preflight average, and an "increaser" group, wherein subjects' post-flight average exceeded their preflight average. The vertical torso translation was not significantly different after exposure to space flight compared to preflight.

Zangemeister *et al.* (1991) demonstrated that normal locomotion performed with the head in a retroflexed position induces alterations in lower limb muscle activity patterns. They concluded that a functional linkage exists between otolith signals generated by various head positions and the muscle activity patterns generated in the lower limbs during locomotion. Appropriate attenuation of energy transmission during locomotion, achieved by the lower limbs' joint configuration coupled with appropriate eye-head-trunk coordination strategies, was demonstrated as being fundamental feature of an integrated gaze-stabilization system during locomotion (Bloomberg and Mulavara 2003; Mulavara *et al.* 2002/2003; Mulavara *et al.* 2005). From this point of view, the whole body is an integrated gaze-stabilization system to which several subsystems contribute, leading to accurate visual acuity during body motion. Given these functional linkages, it can be argued that space flight induces adaptive modification in segmental coordination and disrupt coordinated body movement during post-flight terrestrial locomotion. It follows that active body movement in the unique inertial environment encountered during space flight may require subjects to adaptively acquire novel head-trunk and lower body segmental control strategies. Adaptation to long-duration space flight leads to modified reflexive head stabilization mechanisms; modified transmission characteristics of the shock wave at heel strike; and increased total knee movement during the subsequent stance phase during post-flight walking. These strategies, however, may be maladaptive for

locomotion in a terrestrial 1 g environment leading to impairment of locomotor function during the readaptation period following the return to Earth.

Previous space flight data have shown post-flight increases in vestibulo-spinal reflexes in humans and increased utricular afferent sensitivity to translation shown in toadfish (Reschke *et al*. 1984; Boyle *et al*. 2001). Upregulation of the sensitivity of the utricular afferents after adaptation to 0 g may be manifested in the "increaser" group of astronaut subjects. However, a similar increase in vestibular sensitivity would tend to generate larger head pitch for the same trunk vertical translation during locomotion (Moore *et al*. 2006). A similar increase in head movements in the pitch direction was observed in all subjects who had undergone 30 minutes of adaptation to locomotion while unloaded to 60% of body weight with no changes in trunk vertical translation during locomotion (Mulavara *et al*. 2012). This was not the case for the subjects in the "decreaser" group of astronaut subjects. Data from experiments with labyrinthine-deficient patients and experiments in which galvanic vestibular stimulation (GVS) was used to induce acute vestibular disturbances indicated that a reduction in head movement response could be a voluntary strategic response to reduce sensory conflict (Mulavara *et al*. 2012). Thus, the "decreaser" group of subjects may show an increased weighting of vestibular signals and hence sensory weighting may be a marker of post-flight disturbance. This strategy may also reflect the response of a control system looking for a new equilibrium point. The goal of establishing this new end point would be to reduce potential canal-otolith ambiguities.

The lack of change in vertical trunk translation indicates that the input disturbances to the gaze control system remain unchanged. Taken together, the kinematic and gaze stabilization findings indicate that body load-sensing somatosensory input centrally modulates vestibular input and can adaptively modify vestibularly mediated head-movement control during locomotion. Thus, space flight may cause a central adaptation of the converging vestibular system and the body load-sensing somatosensory system, leading to alterations in head-movement control.

### 3.2.3. Dynamic Visual Acuity

Gaze control orchestrated by the CNS is critical to dynamic visual acuity (DVA), 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). Post-flight 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.

Measures of dynamic visual acuity (DVA) have been used as a diagnostic tool for identifying vestibular dysfunction (Lee *et al.* 1997; Hillman *et al.* 1999; Schubert *et al.* 2001, 2002; Tian *et al.* 2001). However, even persons with healthy vestibular function can experience, under certain conditions, compromised visual performance (Deshpande *et al.* 2013). 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 (Meddick & Griffin 1976; Moseley & Griffin 1986; Boff & Lincoln 1988; Griffin 1990; Demer *et al.* 1993). 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.* (1997) 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 space flight missions and previously employed during the Apollo program.

Decreased DVA performance was demonstrated in astronauts following return from long-duration space flight (Bloomberg and Mulavara 2003; Peters *et al.* 2011). A second-generation test using Landolt C characters instead of numbers also documented decrements in DVA performance as a function of time after flight in crewmembers returning from long-duration space missions (Peters *et al.* 2011) (Figure 6). 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 post-flight recovery period. These results may significantly underestimate the decrements in visual performance that are actually experienced during and immediately following landing because all DVA data (with the exception of one subject) were collected no earlier than 24 hours after landing. Given how rapidly VOR function and gaze control re-adapts the decrement in visual acuity at the actual time of landing was likely much higher than measured during the first postflight data collection session.
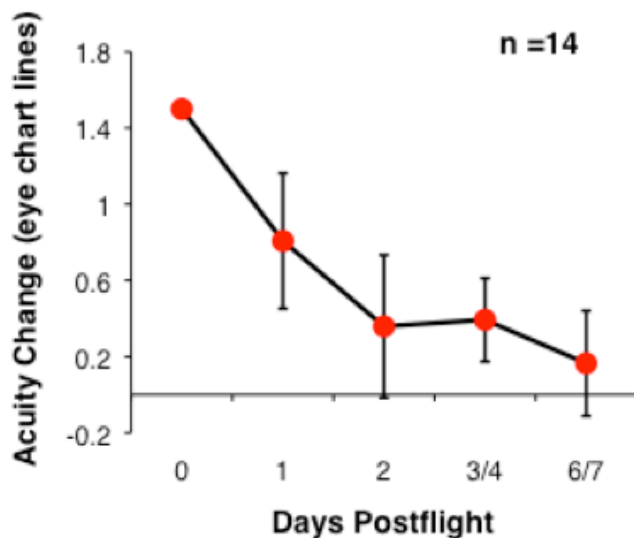
*Figure 6. Dynamic visual acuity data during treadmill walking from 14 crewmembers after return from 6-month ISS flights. Data are normalized to the subjects' preflight DVA values, which are represented on the y-axis at 0. These data show a decrement in postflight walking acuity followed by an improvement in performance during the postflight recovery period.*

Changes in dynamic visual acuity also contribute to functional changes (on the ground) in patients with vestibular disorders (Herdman 1994). For various reasons, physicians often caution patients with vestibular disorders against driving (Cohen *et al.* 2003). 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 (1992) 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 VOR function. As a result, his eye movements were not able to compensate adequately for the motions of his body in turbulent conditions.

### 3.3. Decrements in Jump Performance

Following space flight crewmembers also experience changes in the otolith-spinal reflex mechanisms that are essential for the preprogrammed motor strategies used for impact absorption after a jump. Watt *et al.* (1986) tested Shuttle astronauts during sudden "drops" and reported that all subjects were unsteady post-flight. The otolith-spinal reflex, which helps prepare the leg musculature for impact in response to sudden falls, is dramatically reduced during space flight. Reschke *et al.* (1986) used the Hoffman-reflex to examine the effect of drops on the sensitivity of the lumbosacral motoneuron pool, which is presumably set by descending otolith control signals. A large potentiation of the Hoffman-reflex recorded in the soleus muscle was found beginning approximately 40 ms following an unexpected drop. This potentiation of the Hoffman reflex during drops vanished on the 7th day of space flight. Immediately following space flight, two of four subjects demonstrated a significant increase in potentiation during the drop compared with pre-flight testing.

Shuttle astronauts were also tested pre-flight and post-flight (< 4 hr after return) on voluntary 2-footed downward hops from a 30 cm high step. Motion analysis of the jump

indicated impairment in the ability to coordinate effective landing strategies (Newman *et al.* 1997; Courtine & Pozzo 2004). A decrease in hip flexion and changes in the center of mass position relative to the feet were observed. The majority of crewmembers fell backwards (likely due to a potentiated stretch reflex) on the first of three jumps, and there was a greater use of arms for balance. These data provide further evidence for post-flight changes in motor programming during the jump aerial phase and impaired ability to prepare the limb muscles for the impact phase of the jump.

Other work indicates that space flight may affect proprioception of limb position (see section IV, 2.1.2). Watt *et al.* (1997) found a considerable decline in arm-pointing accuracy while blindfolded during and immediately following space flight. When they performed deep rhythmic knee and arm bends after space flight, subjects reported that floors and walls moved toward them, and that their knees bent more rapidly than intended. This can be partly explained by an abnormal level of muscle spindle receptor activation on return to 1 g, which results in misinterpretation of muscle length and subsequent abnormal flexion. Therefore, altered jumping performance seen post-flight may reflect decrements in limb proprioception sense, combined with altered central interpretation of otolith acceleration cues and vestibulo-spinal reflexes.

### 3.4. Perceptual Changes

#### 3.4.1. Crew Reports

After Shuttle missions, crew members were asked to indicate whether or not they experienced any of the 21 neurovestibular symptoms listed on a standardized questionnaire. It is important to keep in mind the subjective nature of these reports, as well as the possibility that some crewmembers might not have reported truthfully for personal reasons. It is unknown exactly at what point the astronauts actually felt the reported symptoms.

Nevertheless, out of 88 commanders reporting postflight:

> 9.09% reported persistence of illusory motion phenomenon
> 51.1% reported malaise
> 52.2% reported dry heaves
> 52.3% reported stomach awareness
> 60.2% reported sweating
> 61.4% had nausea
> 61.4% vomited
> 61.4% had persisting sensation aftereffects
> 68.1% had blurred vision
> 68.1% had headaches
> 65.9% had vertigo while walking

72.7% had difficulty walking in a straight line
69.3% had vertigo while standing
77.2% noticed clumsiness in their movements

Crewmembers also report a number of perceptual changes after space flight that may hinder their work performance: (a) *modified sensations of movement*, i.e., a feeling that they or the visual surround are moving following a simple head movement in any plane; (b) *sensations of excessive body weight* up to 2 to 2.5 times normal weight or that *objects, when handled, are heavier than normal*; (c) *sensations of greater bodily tilt* when the body is tilted from the vertical axis; and (d) *sensations of forced movement* of the body when turning corners.

Most perceptual disturbances and other symptoms resolve rather quickly, within 48 hours. Others, such as postural ataxia, may last with varying degrees of effect for months. During this prolonged recovery phase, tasks that require integration of multiple sensory inputs, e.g., head tilts while on unstable support surfaces, often reveal an underlying deficit that may not be revealed with more restricted movements. Interaction with the environment can shorten recovery times.

### 3.4.2. Proprioceptive Changes

Overall, the post-flight reports of increased heaviness of static objects suggest that some central rescaling of static pressure systems occurs. A Spacelab D-1 mission required subjects to use higher accelerative shaking forces, which improved their ability to discriminate mass but not weight. Additionally, video recordings of astronauts showed that shaking was faster in-flight compared to preflight and slowed after landing, returning to baseline after three days (Ross *et al.* 1986b). Error in weight or mass perception may be due to a basic failure of reafference or to inadequate monitoring of command signals and inappropriate scaling of afferent signals.

### 3.4.3. Perceived Tilt and Translation

Crews typically report 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. A typical pilot comment is: "That really tumbled my gyros" (see Section IV 1.1). 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 (Parker *et al.* 1985; Reschke *et al.* 1994; Harm *et al.* 1999). One of the most common post-flight illusions is of perceived translation, either of self or surround, during a tilting motion (Harm & Parker 1993). In one of the first post-flight experiments to investigate this phenomenon, a parallel swing was used 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 (Reschke & Parker 1987).

On the basis of these observations, and similar ones reported by Young *et al.* (1984), the otolith tilt-translation reinterpretation hypothesis (OTTR) was proposed. The OTTR hypothesis is based on the premise that interpreting otolith signals as indicating tilt is inappropriate during

space flight (see Section IV, 2.4.6). Therefore, during adaptation to weightlessness, the brain reinterprets otolith signals as indicating translation only. 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 (Merfeld 1996a), while performance during translation closed-loop nulling experiments appears to be improved (Arrott et al. 1990).

An alternative hypothesis proposed by Guedry et al. (1998) 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 also explains the post-flight tilt-translation disruptions described above, as well as the increased immunity to Coriolis stimuli observed following the Skylab missions (Graybiel et al. 1977).

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. (2003) 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 (2003) 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, 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 (Merfeld et al. 1993).

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 an 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.

Some evidence exists that provides insight into the physiological basis of these illusions. For example, in a series of rodent experiments, Ross (1993, 1994, 2000, 2003) 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. (2001) 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. (1986), who found an enormous potentiation of the monosynaptic Hoffman reflex response early after flight in human subjects from the Spacelab-1 mission subjected to linear translational acceleration stimuli. This Hoffman 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 & Martinelli (2003), 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 (Krasnov 1994). Pompeiano (2003) 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 solitarius (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.

### 3.4.4. Otolith Asymmetry

Another underlying mechanisms that may contribute to inflight and postflight disturbances in perception and spatial orientation is natural asymmetry in otoconial mass between the right and left saccule and utricle. These asymmetries would lead to different output signals from the left and right otoliths. On Earth the CNS is thought to compensate for this inherent imbalance between otoliths. However, exposure to a weightless environment may lead to decompensation of this process leading to asymmetrical output from the right and left otolith organs and subsequent disturbances in perception of motion and spatial orientation (Clarke et al. 2013). A study was conducted using Shuttle crewmembers that examined otolith asymmetries as a potential underlying factor leading contributing to inflight and postflight perceptual and motor control disturbances (Clarke et al. 2010). The study utilized the vestibular evoked myogenic potentials (VEMP) as an indicator of otolith saccular function through

measurement of a vestibulo-collic reflex. Results showed a general increase in asymmetry of otolith responses on landing day relative to the preflight baseline data. There was a subsequent reversal in asymmetry within 2-3 days. Recovery back to preflight levels occurred within the first week following the return to Earth. These findings indicate that space flight results in adaptive changes in neural integration of otolith inputs contributing to perceptual illusions during gravitational transitions.

## 3.5. Gaze Changes

### 3.5.1. Vestibulo-Ocular Reflex

Evidence exists that the VOR could be severely compromised during the transition between low Earth orbit and the return to Earth's gravity. Using a gaze stabilization protocol, eye and head movements were recorded from crewmembers inside of the Landing and Entry Helmet during descent (Reschke *et al.* 1999). This protocol required the subject to view a target presented to the subject at a distance of approximately 0.5 m from the eyes. Immediately upon target presentation, vision was occluded and the subject acquired the remembered target. One second later the target was exposed and the subject made any correction to the target with only the eyes. This protocol permitted the determination of the VOR gain. Interestingly, the data showed that the VOR is not functional immediately after landing (Figure 7).
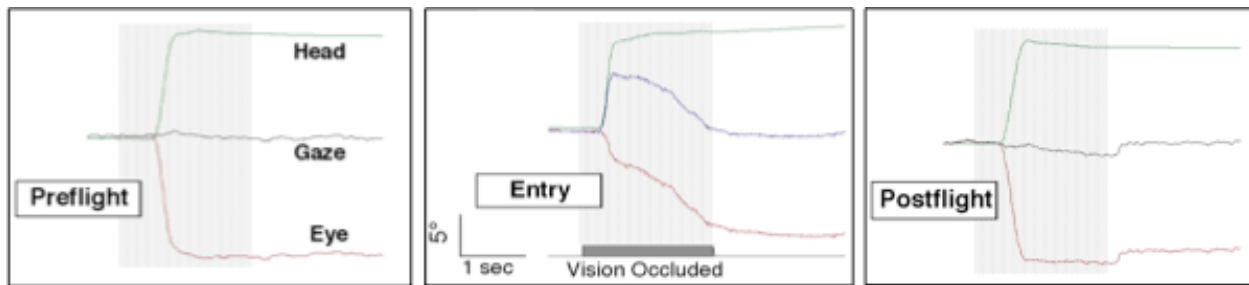


*Figure 7. Gaze stabilization paradigm. The VOR, nearly perfect preflight, is disrupted during entry. The eye is apparently locked with the head rather than moving equally and opposite the head movement (stabilizing vision). Approximately one hour after landing (Postflight) the VOR has returned to normal.*

Experiments during 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 (Oman *et al.* 1993, 1996) and in normal subjects (DiZio & Lackner 1988). 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 (Oman *et al.* 1988). 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.

### 3.5.2. Ocular Counterrolling

The otoliths, detectors of linear acceleration, contribute to eye stabilization and spatial orientation during space flight. In the absence of gravity, head tilt has insignificant meaning, and therefore, torsional eye movements should be minimal or absent. However, statolith input may be reinterpreted. As a result, ocular counter-rolling (OCR) induced by tilt has been investigated before and after space flight as an indicator of otolith adaptation. Head tilt after Gemini missions induced no changes in OCR (Graybiel et al. 1967).

Clément et al. (2007) have reviewed the evidence of changes in OCR during static whole body tilt in postflight studies following Space Shuttle missions, and they noted that the findings are inconsistent. Some studies report decreases in astronauts' OCR after the flight relative to preflight, while others have shown postflight increases of OCR or no changes at all (Reschke et al. 1985; Vogel & Kass 1986; Young & Sinah 1998; Diamond & Markham 1998; Hofstetter-Degen et al. 1993; Moore et al. 2001; Clarke & Kornilova 2007; Kornilova et al. 2011). When averaged across all these space studies, the difference between pre- and postflight OCR measurements was found to be less than 0.6° for body tilt angles ranging from 15-45° (Figure 8). The inconsistency in these results may be due to the various experimental procedures employed, including flash afterimages, flash photography of the eyes, or video-oculography, and to the high variance of the OCR across individuals.
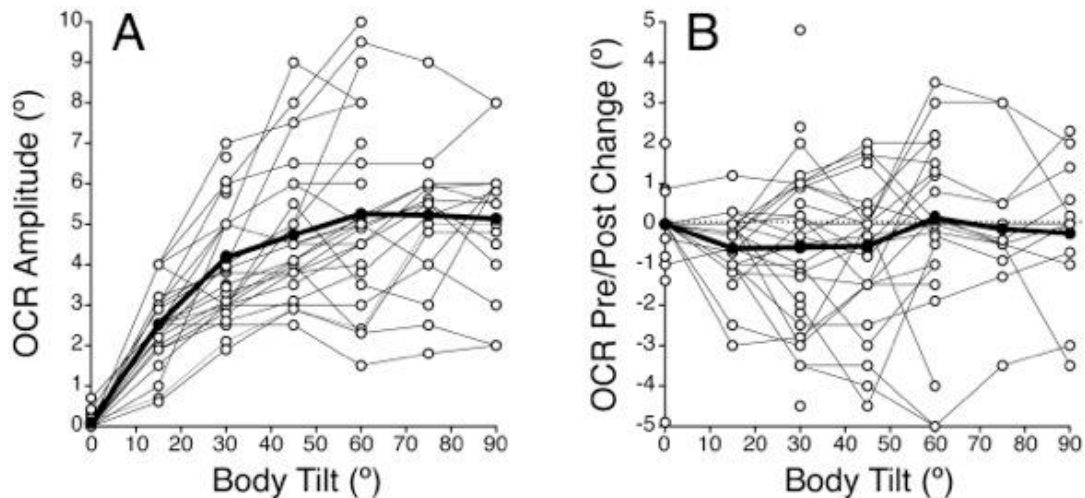


Figure 8. A. Individual (open circles) and averaged (closed circles) OCR amplitude during static whole body tilt recorded preflight in 18 astronauts. B. Differences between pre- and postflight OCR measurements (Clément et al. 2007).

### 3.5.3. Eye Movements during Coriolis and Cross-Coupled Acceleration

As part of the Human Vestibular Function (M-131) study during the three Skylab manned missions, eight crewmembers performed head and body movements during yaw rotation

ranging from 12.5-30 rpm (Graybiel *et al.* 1977). This stimulus generated Coriolis, cross-coupled accelerations, which were at the origin of motion sickness preflight. All crewmembers could perform more head body movements and had reduced motion sickness from flight day 6 and beyond. In addition, 7 out of the 8 crewmembers had reduced motion sickness postflight from the day after landing (R+1) through R+17. The remaining crewmember had mild and severe MS for two of the 3 days at sea following splash-down. The other crewmembers had taken anti-motion sickness medication taken during recovery and no motion sickness.

Other experiments demonstrated that most subjects perceive passive vestibular stimulation to be less provocative on landing day than preflight. For example, 9 of 10 crewmembers tested had no symptoms of motion sickness when exposed to passive yaw rotation or Coriolis acceleration on R+0 (Thornton *et al.* 1987a; Oman *et al.* 1996; Clément *et al.* 1999). In those experiments using passive rotation on R+1 and later, 26 out of 29 crewmembers showed a decreased of susceptibility to MS postflight relative to preflight (Graybiel *et al.* 1977; Wetzig *et al.* 1993; Harm *et al.* 1994; Moore *et al.* 2001). One crewmember was tested using Coriolis and off vertical axis rotation (OVAR) following the 10-day Apollo-9 mission. Reports indicated that the single subject tested had an average susceptibility to motion sickness preflight and that there was an increase tolerance with repeated exposures postflight (Homick & Miller 1975). In another study, 58 crewmembers participating in 16 flights of the Space Shuttle (duration < 11 days) were also tested during Coriolis (12.5-30 rpm) and during OVAR (20 rpm up to 30° tilt) before (L-3 to L-6 months) and after (R+0 to R+3 months) their space flight. This experiment focused on predictive values of ground tests (Homick *et al.* 1987). Two crewmembers tested immediately postflight showed reduced motion sickness to Coriolis (up to several weeks), although one subject was found to be hypersensitive on landing day (Thornton *et al.* 1987a). Recent experiments indicate that velocity storage (Cohen *et al.* 1977), the central integration of semicircular canal signals, is attenuated during exposure to nonterrestrial gravitoinertial force backgrounds and that this effect carries over to the postflight period (DiZio & Lackner 1988; Oman & Balkwill 1993; Oman *et al.* 1996). Converging evidence from ground-based and space flight experiment also points to a relation between motion sickness and the properties of the velocity storage (DiZio & Lackner 1991; Oman 1998; Dai *et al.* 1996, 2010) Perception of the vertical and of body angular movements indicate that spatial integration of canal afferent signals is disturbed after adaptation to microgravity (Clément *et al.* 2007, 2001), suggesting that velocity storage is reduced.

### 3.5.4. Eye movements during Linear Acceleration

Two subjects exposed to transient lateral acceleration 3-5 hours after the landing of the SL-1 mission demonstrated smaller torsional amplitudes than three of the four preflight measures of sinusoidal ocular torsion for these subjects. Torsional amplitude in these subjects steadily increased over most of the post-flight tests, but changes were not statistically significant because of high variability in the preflight measurements (Arrott & Young 1986). Y-axis linear translation enhanced horizontal eye movements in crewmembers 2-3 days after landing (Parker *et al.* 1986). These results are consistent with the OTTR hypothesis, which predicts reduced eye torsion immediately after landing due to reinterpretation of otolith signals as linear translation (Parker *et al.* 1985; Liao *et al.* 2011).

In two recent studies, eye movements and perceived motion were evaluated in astronauts returning from Space Shuttle missions during OVAR (Clément & Wood 2013) and during short-radius centrifugation (Clément & Wood 2014). No changes were seen on the compensatory eye movements to these linear accelerations between pre- and post-flight. However, the crewmembers reported an overestimation of the sensation of roll tilt (but not pitch tilt) and an overestimation of the sensation of translation immediately post-flight. These results confirm that some VORs elicited during passive motion may not be altered by short-duration space flight, or may readapt very quickly, and that the resolution of sensory conflict associated with post-flight recovery involves higher-order neural processes (Holly *et al.* 2010).

### 3.6. Decrements in Functional Performance

### *3.6.1. Functional Mobility*

Pre- and postflight functional mobility assessment was performed on ISS crewmembers to determine their ability to complete challenging locomotor maneuvers similar to those encountered during an egress from a space vehicle (Mulavara *et al.* 2010). To perform the Functional Mobility Test (FMT) subjects walked at a self-selected pace through an obstacle course set up on a base of medium density foam that increased the challenge of the test. There was a 48% increase in time to traverse the course one day after landing, and recovery of function took an average of 15 days to return to within 95% of their preflight level of performance (Figure 9).

The results also showed that post-flight recovery can be divided into two processes: rapid strategic learning over the six trials on the first day after return, and a slower process taking over 2 weeks to recover to a pre-flight level of performance. It is believed that training can promote or enable these strategic or early learning responses for facilitating faster re-adaptation to Earth's 1-g environment on return from space flight. Additionally, a significant positive correlation between measures of long-term recovery and early motor learning (strategic learning) indicating that the two types of recovery processes influence an astronaut's ability to re-adapt to Earth's gravity environment. Early motor learning helps astronauts make rapid modifications in their motor control strategies during the first hours after landing. Further, this early motor learning appears to reinforce the adaptive realignment, facilitating re-adaptation to Earth's 1-g environment on return from space flight.
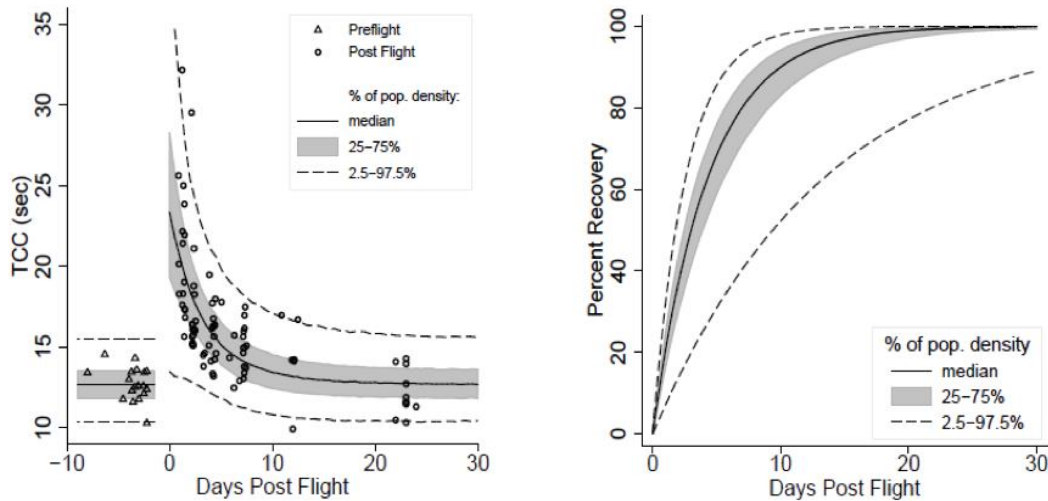
*Figure 9. Left: scatter plot of time to complete the course (TCC) for 18 long-duration subjects showing a 48% increase in time to traverse the obstacle course one day after landing. Right: Recovery of function took an average of 15 days to return to within 95% of their preflight level of performance.*

Adaptation to different gravitational environments may affect planetary extravehicular activities during the initial adaptation period due to postural and locomotor dysfunction. These alterations may also lead to decrement in the ability to multi-task along with increasing the metabolic costs of ambulation. A recent study examined subjects walking on a destabilizing support surface using a treadmill mounted on a six-degree-of-freedom motion base that provided an oscillating support-surface during walking (Peters *et al.* 2013b). Results demonstrated that measures of locomotor stability, cognitive load, and metabolic cost were all significantly greater during support-surface motion that during baseline walking conditions and showed a trend toward recovery to baseline levels during locomotor adaptation. These decrements are operationally meaningful because they indicate broader functional implications for postflight locomotor instability (Brady *et al.* 2009, 2012). Until recently, locomotor adaption to discordant sensory conditions has been characterized primarily in terms of impact on the underlying mechanisms contributing to locomotor stability. These results indicate that uncoordinated walking during periods of adaptive change may also come at significant cognitive and metabolic costs to the crew. Cognitive load increases and metabolic cost rises because of new demands on attention and additional physical work required to maintain balance while walking. Energetic cost is a key contributor to the duration and intensity of EVAs performed by suited astronauts, and previous research on suited locomotion has explored the effects of load, slope, and walking vs. running (Carr & Newman 2007a, 2007b). Metabolic cost associated with locomotor instability is a factor that should be accounted for in the continuing efforts to improve extravehicular suit design.

### 3.6.2. Functional Tasks

To understand how changes in physiological function affect functional performance, an interdisciplinary pre- and post-flight testing regimen, Functional Task Test (FTT), was developed

to systematically evaluate both astronaut functional performance and related physiological changes (Spiering *et al.* 2011; Arzeno *et al.* 2013; Ryder *et al.* 2013; Bloomberg *et al.* 2015a). Ultimately this information will be used to assess performance risks and inform the design of countermeasures for exploration class missions. This FTT study was conducted on Shuttle and ISS crewmembers before and after 6-month expeditions and is currently being conducted for 1-year expeditions. Additionally, in a corresponding study, the FTT protocol was used on subjects before and after 70 days of 6° head-down bed-rest as an analog for space flight. Bed-rest provides the opportunity to investigate the role of prolonged axial body unloading in isolation from the other physiological effects produced by exposure to microgravity (Reschke *et al.* 2009). Therefore, the bed rest analog allowed the investigation of the impact of body unloading on both functional tasks and on the underlying physiological factors that lead to decrement in performance and then compare those with the results obtained in the space flight study.

Functional tests included ladder climbing, hatch opening, jump down, manual manipulation of objects and tool use, seat egress and obstacle avoidance, recovery from a fall, and object translation tasks (Bloomberg *et al.* 2015a). Physiological measures included assessments of postural and gait control, dynamic visual acuity, fine motor control, plasma volume, heart rate, blood pressure, orthostatic intolerance, upper- and lower-body muscle strength, power, endurance, control, and neuromuscular drive. ISS crewmembers were tested three times before flight, and 1, 6, and 30 days after landing. Subjects in bed rest studies were tested three times before bed rest and immediately after getting up from bed rest as well as 1, 6, and 12 days after reambulation.

Astronaut data showed that functional tests requiring a greater demand for dynamic control of postural equilibrium (i.e., fall recovery, seat egress and obstacle avoidance during walking, object translation, jump down) showed the greatest decrements in performance (Bloomberg *et al.* 2015a). Functional tests with reduced requirements for dynamic postural stability (i.e., hatch opening, ladder climb, manual manipulation of objects and tool use) showed less reduction in performance. Similarly, subjects exposed to prolonged bed rest (> 20 days) showed the same trends in performance change as astronauts, namely a reduction in performance on functional tests requiring a greater demand for dynamic control of postural equilibrium. For both spaceflight and bed rest subjects these changes in functional performance were paralleled by similar decrements in physiological tests designed to specifically assess postural equilibrium and dynamic gait control.

Taken together, the space flight and bed rest results indicate that the unloading of body support structures (major postural muscles) that is experienced during space flight plays a central role in post-flight alteration of functional task performance and balance control. These data point to the importance of providing significant axial body loading during in-flight treadmill and resistive exercise. In addition, these data indicate that balance training should be used to supplement current in-flight aerobic and resistive exercise activities.

### 3.6.3. Field Test

Testing of crew responses following long-duration flights has not been previously possible until a minimum of +24 hours after landing. As a result, it has not been possible to determine the trend of the early recovery process, nor has it been possible to accurately assess the full impact of the decrements associated with long-duration flight. To overcome these limitations, both the Russian and U.S. programs have implemented joint testing at the Soyuz landing site. This ISS research effort has been identified as the Field Test, and represents data collect on NASA, Russian, ESA, and JAXA crews.

The primary goal of this research is to determine functional abilities associated with long-duration space flight crews beginning as soon after landing as possible on the day of landing (typically within 1 to 1.5 hr). This goal has both sensorimotor and cardiovascular elements. To date, a total of 15 subjects have participated in a 'pilot' version of the full 'field test'. The full version of the 'field test' will assess functional sensorimotor measurements included hand/eye coordination, standing from a seated position (sit-to-stand), walking normally without falling, measurement of dynamic visual acuity, discriminating different forces generated with the hands (both strength and ability to judge just noticeable differences of force), standing from a prone position, coordinated walking involving tandem heel-to-toe placement (tested with eyes both closed and open), walking normally while avoiding obstacles of differing heights, and determining postural ataxia while standing (measurement of quiet stance). A number of these tests have been utilized and tested for sensitivity and specificity in a relatively large cohort of normal and clinical patients populations (Cohen *et al.* 2012a, 2012b, 2013, 2014; Peters *et al.* 2012b; Peters *et al.* 2013a, Mulavara *et al.* 2013)

Sensorimotor performance has been obtained using video records, and data from body worn inertial sensors. The cardiovascular portion of the investigation has measured blood pressure and heart rate during a timed stand test in conjunction with postural ataxia testing (quiet stance sway) as well as cardiovascular responses during sensorimotor testing on all of the above measures. Motion sickness data associated with each of the postflight tests has also been collected. When possible a rudimentary cerebellar assessment was undertaken. In addition to the immediate postlanding collection of data, postflight data has been acquired twice more within 24 hours after landing and measurements continue until sensorimotor and cardiovascular responses have returned to preflight normative values (approximately 60 days postflight).

The level of functional deficit observed in the crew tested to date is more severe than expected, clearly triggered by the return to gravity loads immediately after landing when the demands for crew intervention in response to emergency operations will be greatest. Measureable performance parameters such as ability to perform a seat egress, recover from a fall or the ability to see clearly when walking, and related physiologic data (orthostatic responses) are required to provide an evidence base for characterizing programmatic risks and the degree of variability among crewmembers for exploration missions where the crew will be unassisted after landing. Overall, these early functional and related physiologic measurements

will allow the estimation of nonlinear sensorimotor and cardiovascular recovery trends that have not been previously captured (Reschke *et al.* 2015).

### *3.6.4. Navigation*

To quantify performance in orienting during free walking after space flight, astronaut subjects were asked to walk, preflight and post-flight, a previously seen triangular path with normal vision and vision occluded (Glasauer *et al.* 1995). The path, marked on the ground by a cross at each corner, consisted of a right triangle with two legs 3-m long. The trajectories of three infrared-reflective markers fixed on a helmet were recorded using a video-based motion analysis system. Subjects showed inter-individual differences, especially for directional deviations from the path, in the vision-occluded condition even preflight; the characteristics of these differences persisted throughout all experimental sessions. The absolute directional errors turned out to be larger post-flight, which means that subjects had larger directional errors but in different directions. In the post-flight condition, however, there was a trend to a larger underestimation of the angle turned at each corner. In contrast to directional errors, the length of the legs walked was similar pre- and post-flight. These data suggest that the perception of self-displacement during turning, but not during linear motion, was changed by the stay in weightlessness. A possible explanation could be the development of a mismatch between information from otoliths and semicircular canals during whole-body turns in microgravity. This change in canal-otolith interaction may underlie the disturbances in locomotion experienced by returning astronauts.

## 3.7. Decrements in Manual Control

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 (Arrott & Young 1986) and/or longitudinal (Merfeld *et al.* 1996b) body axes. Four of the seven subjects tested showed improved post-flight performance on the nulling task. Also, Merfeld *et al.* (1996a) tested the early post-flight 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 ground-based experiments (Park *et al.* 2006; Wetheim *et al.* 2001) showed that when subjects must resolve tilt-translation ambiguities, and are naïve to the possible motion, large misperceptions of tilt could result.

## 3.8. Impact of Vestibular Changes to Orthostatic Intolerance

Historically, factors that have been thought to contribute to post-space flight orthostatic intolerance (PSOI) include space flight-related volume depletion (Fischer *et al.* 1967; Johnson *et*

*al.* 1977; Bungo *et al.* 1985; Charles & Lathers 1991) and excessive venous pooling in the lower extremities (Johnson *et al.* 1976; Buckey *et al.* 1992) or splanchnic circulation. More recent findings, however, suggest that abnormalities in autonomic cardiovascular control, including a loss of carotid-cardiac baroreflex range and slope during and after space flight (Fritsch *et al.* 1992; Fritsch-Yelle *et al.* 1994) and a deficit in peripheral vasoconstriction in the upright position on landing day may play a primary role in PSOI (Buckey *et al.* 1996; Fritsch-Yelle *et al.* 1996). These autonomic factors have been recently reemphasized given the finding that little correlation exists between deficits in plasma volume and deficits in orthostatic tolerance in returning astronauts. The mechanisms underlying the autonomic abnormalities associated with PSOI, however, remain poorly understood.

Over the past several years, much evidence has accumulated to suggest that the vestibular organs can provide "-" signals that supplement feedback information provided by baroceptors in maintaining orthostatic tolerance (Doba & Reis 1974; Gillingham *et al.* 1977, Essandoh *et al.* 1988; Satake *et al.* 1991; Yates 1992; Previc 1993; Yates *et al.* 1993; Convertino *et al.* 1997; Ray *et al.* 1997; Shortt & Ray 1997; Woodring *et al.* 1997; Yates & Kerman 1998; Serrador *et al.* 2009a, Serrador *et al.* 2009b). The neuroanatomic and neurophysiologic bases for vestibular contributions to autonomic cardiovascular control have recently been reviewed thoroughly by Yates and colleagues (Yates 1992, 1998; Yates & Kerman 1998; Yates & Miller 1996, 1998; Yates *et al.* 1998).

The following, taken together, provide strong evidence that changes in vestibular (and especially otolith) function during space flight contribute to PSOI: (1) changes in otolith function (Vogel & Kass 1986; Young *et al.* 1986) and structure (Ross 1993, 1994) have been described and verified in multiple studies during and after space flight; (2) signals from intact otolith organs clearly contribute to sympathetically mediated peripheral vasoconstriction in animals (Doba & Reis 1974; Woodring *et al.* 1997; Yates 1992, 1998; Yates & Kerman 1998; Yates & Miller 1998) and likely contribute to sympathetically mediated peripheral vasoconstriction in humans (Essandoh *et al.* 1988; Normand *et al.* 1997; Ray *et al.* 1997; Shortt & Ray 1997); and (3) the key autonomic defect associated with PSOI in most returning crewmembers is inadequate sympathetically mediated peripheral vasoconstriction (Buckey *et al.* 1996; Fritsch-Yelle *et al.* 1996). In spite of all of this evidence, however, the precise role of vestibular-autonomic factors in PSOI remains to be defined. Further ground-based studies using both labyrinthine-deficient and -intact humans and animals will be required before any definitive treatment or prophylactic regimens can be designed based on an assumption of underlying vestibular-autonomic pathology.

## V. COUNTERMEASURES

Space Motion Sickness (SMS)

Most of the countermeasures to adverse effects of space flight on the human nervous system have been used to reduce SMS. Prevention would be the best countermeasure but so far has shown little success. The disruptive nature of SMS has led to a variety of approaches for preventing or controlling this malady. Only limited success has been achieved to date. Research in this area has proceeded along four broad lines of inquiry, which has namely been selection screening, pharmacologic treatment, training, and the use of mechanical or electrical devices.

Attempts to prevent space motion sickness have included crew selection with a high tolerance to vestibular stimulation. Khilov (1974) contended that the most suitable individuals should exhibit the smallest magnitude in response to various vestibular tests. Suitability can be further assessed by repeating these tests after administration of chloral hydrate, which removes the cortical inhibition of vestibular reactions. Applicants to the U.S. Astronaut Corps are not screened for motion sickness resistance. Although the Russian space program uses this process, it has been met with little success (Lapayev & Vorobyev 1986; Clément *et al.* 2001). Moreover, crewmembers who have completed preflight Coriolis tests have shown no correlation between test tolerance and susceptibility to SMS (Reschke 1990).

### 1. PHARMACOLOGICAL COUNTERMEASURES

Many drugs have been tested for their effectiveness against motion sickness. Although some drugs have proven somewhat effective, no drug or drug combination has been identified that protects all individuals.

### 1.1. Drug Classes

The mechanism(s) of action of the effective anti-motion sickness drugs is unclear, but it has been noted that the action(s) responsible for their anti-motion sickness efficacy tends to differ from the drug's primary action (Money 1970). Numerous studies have found scopolamine, an anticholinergic (parasympatholytic) drug, to be effective in treating motion sickness (Wood & Graybiel 1968, 1970, 1972; Graybiel *et al*. 1976, 1981; Graybiel & Knepton 1977; McCauley *et al*. 1979; Laitinen *et al.* 1981; Shashkov & Sabayev 1981; Homick *et al*. 1983; Noy *et al*. 1984; Levy & Rapaport 1985; Pyykkö *et al.* 1985; van Marion *et al.* 1985; Grigoriev *et al.* 1986; Offenloch *et al.* 1986; Wood *et al*. 1986, 1987a; Attias *et al.* 1987; Graybiel & Lackner 1987; How *et al*. 1988; Karkishchenko 1989; Shupak *et al.* 1989; Woodard *et al.* 2014). Although most of the antihistamines tested for anti-motion sickness properties have had some benefit, they tend to be less effective than scopolamine. Promethazine, the most effective of the antihistamines, approaches scopolamine in efficacy (Wood & Graybiel 1972). The few sympatholytic drugs that are effective against motion sickness are of marginal benefit and have less effect than the least effective antihistamine (Wood & Graybiel 1968). The combination of a parasympatholytic drug (scopolamine) and a sympathomimetic has also been more effective than these classes of drugs taken alone.

Anti-motion sickness drug research has been reviewed by Wood (1979, 1990). The vast majority of anti-motion sickness drugs have been given orally. However, the complications of oral medications force frequent dosing and the use of secondary medications via other routes of administration to overcome decreased absorption (Chess et al. 1975; Reason & Brand 1975; Graybiel et al. 1976; McCauley et al. 1979; Graybiel et al. 1981; Homick et al. 1983; Becker et al. 1984; Levy & Rapaport 1985; Pyykkö et al. 1985; van Marion et al. 1985; Offenloch et al. 1986; Attias et al. 1987; Graybiel & Lackner 1987; Wood et al. 1987b; How et al. 1988; Bagian 1991; Davis et al. 1993a, 1993b). The occurrence of side effects also precludes the effective use of many of these drugs. Two newer classes of antiemetic drugs, 5HT3 and NK1 receptor antagonists, may be promising candidates for the treatment of motion sickness (Stott et al. 1989; Koch et al. 1994; Gardner et al. 1995).

## 1.2. In-Flight Medication

A reported 28–30% of all Shuttle crewmembers received medication for relief of SMS during flight (Santy & Bungo 1991). In the U.S. program, scopolamine, scopolamine with dextroamphetamine (scop-dex), promethazine, promethazine with ephedrine, metoclopramide, naloxone, and Compazine have all been used to treat SMS, with varying degrees of success (Graybiel 1980; Thornton et al. 1987a; Davis et al. 1993a, 1993b; Bagian & Ward 1994). Reports are available on the prophylactic and in-flight use of scop-dex taken orally (Davis et al. 1993a). Only 3 of 19 crewmembers who took this medication experienced no SMS symptoms.

Intramuscular (IM) promethazine has been used successfully to treat SMS symptoms. Davis et al. (1993b) reported that of 20 crewmembers given 25–50 mg of promethazine IM (dose adjusted for body weight) on flight day 1, 25% were still classified as "sick" on the second flight day. In contrast, 50% of the 74 crewmembers reporting SMS on the first day of flight who did not receive promethazine, or received other anti-motion sickness medications, were still "sick" on flight day 2. Ninety percent of those who received IM promethazine reported relief from SMS symptoms within 1 to 2 hours of dosing and only three crewmembers needed a second dose. Three of the IM promethazine recipients reported drowsiness after administration, but the injection is often given immediately before the sleep period. An IM injection of 25–50 mg of promethazine is now the recommended treatment for moderate to severe cases of SMS in the U.S. space program, whereas oral and suppository routes are used for less severe symptoms. Some crewmembers have taken a prophylactic combination of promethazine and dextroamphetamine before launch.

The variable success of anti-motion sickness drugs administered during flight may be due to changes in drug absorption or metabolism by factors such as dehydration, reduced gastrointestinal motility, changes in body chemistry, changes in cabin pressure, and disruption of normal sleep/wake cycles. The concomitant administration of medications for other indications is another confounding factor (Santy & Bungo 1991). The recent success of IM promethazine administration is encouraging. Questions still remain, however, as to whether the effectiveness of promethazine is due to its pharmacologic effect or its route of administration (Bagian 1991).

## 2. TRAINING AND REHABILITATION

### 2.1 Vestibular Training

Vestibular training has been used in attempts to prevent or control the symptoms of SMS. Vestibular training techniques investigated thus far have been based on one of two suppositions: (a) adaptation to stressful motion can be hastened through previous exposure to conflicting sensory inputs; or (b) symptoms can be avoided by learned control of autonomic responses.

Lapayev and Vorobyev (1986) have hypothesized that motion sickness susceptibility is proportional to the ratio of signals from the vestibular system and other sensory (e.g., visual, proprioceptive) systems. They propose that the most effective method of increasing tolerance to motion sickness is to train the vestibular system while stimulating the other senses. The Russian space program primarily uses Coriolis and cross-coupled angular acceleration as preflight vestibular training. However, this method does not duplicate the sensory conflicts or fluid shifts encountered in weightlessness. Aizikov et al. (1991) observed that using a predetermined sequence of muscle tension and relaxation increased tolerance to experimentally induced motion sickness by reducing the number of symptoms and shortening the recovery time. These investigators theorize that the afferent propriotactile information generated by the muscle-tension regimen provides enough information on body position to override coincident, possibly inaccurate, vestibular information.

### 2.2. Preflight Adaptation Training

Training devices and procedures to adapt astronauts to the sensory-stimulus rearrangements of microgravity before flight are being developed in the US. Preflight adaptation training is based on the following postulates: (a) that microgravity rearranges sensory stimuli and astronauts adapt to the rearranged stimuli (sensory conflict theory); (b) that adaptation may result from sensory compensation, reinterpretation of stimuli, or both (sensory compensation and OTTR hypotheses) (see Section IV, 2.4.6); and (c) that people can learn and store perceptual, sensory, and sensorimotor responses appropriate to different sensory stimulus conditions, and can learn to invoke these alternative responses when necessary.

Two training devices are used to provide a variety of stimulus rearrangements and train sensorimotor reflexes: the device for orientation and motion environments (DOME) that achieves graviceptor stabilization, and the tilt-translation device (TTD) that produces graviceptor-visual rearrangement. Theoretically, training with these devices would produce the necessary responses to weightlessness and for the return to a 1-g environment, such as compensatory eye movements, postural-muscle reflexes, and self-motion and orientation experiences in relation to visual scene movements.

Ground-based studies using the TTD trainer have revealed that a 270° phase relation between tilt and surround-motion in the TTD best supports reinterpretation of otolith signals as

linear translation (Reschke *et al.* 1988; Harm & Parker 1993, 1994). Exposure to this profile also results in decreased compensatory eye movement gain, net gaze compensation, and decreased postural stability (Michaud *et al.* 1989; Paloski *et al.* 1990; Harm *et al.* 1991; Harm & Parker 1993). These results are consistent with the OTTR model of sensory adaptation and are consistent with observations of astronauts and cosmonauts during or after flight.

Flight investigations involving these training devices thus far have focused on providing an experience of sensory rearrangement that results in illusions of linear or angular self- or surround-motion. The primary purpose of these studies is to teach astronauts to describe perceptual phenomena systematically by using a quantitative "motion perception vocabulary" related to anatomy and physiology so that they can properly describe perceptual illusions.

Post-flight training on the TTD has provided evidence that the simulated perceptual experiences are similar to those experienced in-flight. SMS symptoms and visual disturbances have been reelicited, and perceptual illusions of linear self-motion and tilt angle are intensified relative to preflight stimulation (Harm & Parker 1993; Harm *et al.* 1999). These results generally support the OTTR model of sensory adaptation to microgravity and suggest that the training devices can simulate the appropriate sensory rearrangements. Moreover, crewmembers who participated in this study showed an average 33.5% improvement in SMS symptoms compared with those who did not participate (Harm *et al.* 1999).

## 2.3. Sensorimotor Adaptability Training

Research is currently being conducted to develop a comprehensive sensorimotor adaptability (SA) training program as a countermeasure to facilitate rapid adaptation to novel gravitational environments and readaptation to Earth's gravity (Bloomberg *et al.* 2015b). The human brain is highly adaptable, enabling individuals to modify their behavior to match the prevailing environment. It has been previously shown that subjects trained to adapt to varied sensorimotor challenges can adapt faster to new sensory environments that they have never experienced before (Roller *et al*. 2001; Cohen *et al*. 2005; Mulavara *et al*. 2009; Roller *et al*. 2009; Seidler *et al* 2006;). This is a process known as adaptive generalization that allows you to enhance the ability to "learn how to learn" to adapt to novel environments (Krakauer, 2006; Seidler 2010; Bloomberg *et al*. 2015b).

By applying these motor-learning concepts for training astronauts these training programs can enhance their ability to rapidly adapt their behavioral responses following a gravitational transition. To minimize cost and demands on crew time current training concepts are integrated SA training with existing exercise activities, namely treadmill walking. The SA training program being developed entails manipulating the sensory conditions of treadmill exercise to systematically and simultaneously challenge multiple sensorimotor systems while conducting nominal exercise activities. To provide SA training investigators have mounted a treadmill on a six degree-of-freedom motion base to produce variation in the support surface offering subjects balance challenges during walking (Peters *et al.* 2012; Peters *et al.* 2013; Brady *et al.* 2009). Additional sensorimotor challenges are provided by exposing subjects to variation in visual input during walking using a projected virtual scene that produces variation in visual flow

(Richards *et al.* 2004; Mulavara *et al.* 2005; Nomura *et al.* 2005; Richards *et al.* 2007; Bucello-Stout *et al.* 2008; Brady *et al.* 2012). Bloomberg *et al.* (2015b) have reviewed several studies that have shown that subjects who received SA training adapted faster than controls when presented with a novel discordant sensory environment because they were able to apply adaptive skills that were learned during their earlier training sessions. Importantly, the training improved performance across a number of modalities including enhanced locomotor function and increased multi-tasking capability when walking in a novel, discordant sensory environment not previously experienced by the subjects. This improved performance could be retained over a 6-month period and perhaps longer, indicating that a component of this training could take place before long-duration missions (Batson *et al.* 2011).

Preflight adaptability training could play a central role in facilitating crewmember adaptive response to new gravitational environments in support of both short and long-duration space flight. Given that training may be retained for many months preflight training countermeasures would probably be sufficient to increase adaptability, even for long-duration flight. Therefore one can conceive of this training more in terms of a preflight "inoculation" that will not require significant amounts of crew time preflight and may only require infrequent "booster" training to maintain the training effect. Finally, a collateral benefit of the application VR technology, in this context, will be to make training programs more interesting, ultimately leading to increased adherence to prescribed training regimens.

## 2.4. Biofeedback Training

The autonomic nervous system initially responds to motion-induced stress through sympathetic activation followed by parasympathetic activation. If nausea and vomiting are parasympathetic reactions to sympathetic activation, then motion sickness symptoms might be prevented by training an individual to maintain autonomic regulation at baseline (Cowings *et al.* 1986).

Autogenic feedback training (AFT) combines cognitive imagery and body exercises to produce a desired change in autonomic activity. Sensory feedback regarding information about selected autonomic activities is provided to the subject through visual or auditory cues (Cowings 1990). Two crewmembers in the U.S. Shuttle program performed AFT before flight and two other crewmembers on the same flight served as untrained controls. During flight, the crewmember who showed mixed success in achieving autonomic control during training experienced one severe episode of SMS. Limited space flight testing showed that a crewmember exhibiting greater autonomic control during training before flight reported no severe symptoms. Two untrained crewmembers had multiple episodes of severe symptoms despite the administration of anti-motion sickness drugs (Cowings 1990).

Because AFT does not change the perception of vestibular stimulation, this type of training must interrupt the autonomic response after the sensory conflict has already occurred. Therefore, AFT and parasympatholytic drugs like scopolamine may achieve the same effect but through different mechanisms. AFT reduces sympathetic activity, thereby eliminating the parasympathetic reaction and its resultant symptoms. Scopolamine reduces the

parasympathetic response to the increased sympathetic activity that has already occurred (Cowings *et al.* 1986).

## 2.5. In-Flight Exercise

Physical exercise has been a critical component of countermeasures for long-duration flights. The ISS exercise program consists of both resistive and aerobic exercise.  Aerobic exercise has been performed on both the Treadmill Vibration Isolation System (TVIS) and the Cycle Ergometer with Vibration Isolation System (CEVIS) and now more recently using the Combined Operational Load Bearing External Resistance Treadmill (COLBERT or T2). For resistive exercise the interim Resistive Exercise Device (iRED) was initially implemented on the ISS but this system had some limitations including limited loading and resistance that was nor constant. The newer resistance exercise device named the Advanced Resistive Exercise Device (ARED) utilizes vacuum cylinders and inertial flywheels to simulate constant mass and inertia of free weight exercise and provides twice the loading of the iRED. In addition to attenuating loss of bone mineral density and muscle mass (Smith *et al.* 2012) crewmembers that exercised on the ARED also has less decrement in postflight postural stability and agility scores compared to subjects using the iRED (Wood *et al.* 2011). The increased body loading during ARED exercises may have provided greater postural challenges during exercise improving postflight balance performance.

## 2.6. Head Movements during and after Reentry

The process of readapting to Earth's gravity may be facilitated at the time of reentry when crewmembers perform systematic head movements. Because of operational constraints, scientific study at this time has not been possible, but anecdotal reports from Shuttle crewmembers have indicated that performing head movements that slowly increase in amplitude can minimize motion illusions and motion sickness. The head movements were performed in the yaw plane initially and then in the pitch and/or roll planes, using progressively larger head tilts. Each crewmember should only perform movements at amplitudes and rates that he or she can tolerate at the time, but crewmembers should not restrict head movements too much or they may have problems when they must move to exit the spacecraft. The configuration of crewmembers in the Soyuz at landing, the volume of the spacecraft, and the higher G profile makes moving the head systematically more difficult than it was in the Shuttle, but making systematic head movements during and after reentry is still recommended to crewmembers.

## 2.7. Postflight Balance Rehabilitation Therapy

Balance rehabilitation therapy is the general name for an exercise-based program for reducing the symptoms of disequilibrium and dizziness associated with vestibular disease or disorder. A common neuro-otological approach for managing such symptoms is to prescribe medication that suppresses vestibular function. However, in the long term, such suppressants can interfere with a person's ability to make necessary adaptations. In addition, many of these medications cause drowsiness that may limit a person's ability to be active. Medications, with their side effects, can be avoided by using balance rehabilitation therapy instead.

Vestibular rehabilitation therapy (VRT) is a type of balance rehabilitation therapy. It includes specific exercises that can eliminate or significantly reduce symptoms by promoting CNS compensation for inner-ear deficits. The program is designed to achieve these goals: (a) decrease dizziness and visual symptoms; (b) increase balance and walking functions; and (c) increase general activity levels. The program may include exercises for: (a) coordinating eye and head movements; (b) stimulating the symptoms of dizziness in order to desensitize the vestibular system; (c) improving balance and walking ability; and (d) improving fitness and endurance. Exercises vary depending on the type of symptoms. Balance retraining exercises are designed to achieve steadier walking and standing through improvements in coordination of muscle responses and organization of sensory information (e.g., vision, proprioception). Such treatment is part of the "post-flight reconditioning" of astronauts for 2 hours each day after long-duration space flight. Reconditioning specialists supervise individualized post-flight reconditioning activities, adjusting the level of task difficulty according to the crewmember's level of balance recovery. Most of the activities benefit many body systems even if they target specific functions (Wood *et al.* 2011).

The exercises selected for post-flight reconditioning are based on activities of daily living that crewmembers have reported to be challenging, such as bending over to pick up an object, stooping down to tie one's shoes, and tilting the head backward. Signs of sensorimotor deconditioning are making wide turns, having difficulty changing direction, and making deliberate and slow motions that involve coordination of body segments. Slowed reaction times, difficulty in judging distances, and misperception of force also impair crewmembers' abilities to perform their normal activities.

Post-flight reconditioning activities progress from lower risk to higher risk and simple to complex as crewmembers master particular skills and as particular movements become less provocative. Some exercises are performed every day and others are performed every other day. Posture and stability exercises are performed every day while standing. They include head movements in different planes, toe touches followed by hyperextensions, and trunk twists. Standing with both legs on a stable surface progresses to standing on one leg and standing on an unstable surface. Because mobility facilitates the resolution of sensorimotor symptoms after space flight, astronauts are encouraged to walk as much as possible, beginning on landing day. The limits of the individual's motion tolerance are continually challenged; a "walking toe touch" is one of the most provocative activities. Some activities involve catching and throwing balls of increasing weight, sometimes while walking or shuffling.

Reconditioning specialists and flight surgeons use quantitative measures to evaluate post-flight recovery of each crewmember. Posture is assessed by computerized dynamic posturography and sensory organization tests, including some performed with dynamic pitch head tilts. Agility is measured by testing crewmembers' ability to move forward, backward, and to either side around cones on the floor. Preflight and post-flight tests of posture and agility are used to measure the effectiveness of countermeasures such as in-flight exercise.

## 3. MECHANICAL DEVICES

Various mechanical and electrical devices have been explored in the former Soviet Union to alleviate the symptoms of space motion sickness. The mechanical devices are designed to prevent the complete adaptation of the body to weightlessness by counteracting deconditioning during long missions as well as relieving motion sickness symptoms during the first days of flight. The mechanisms in which electrical devices operate are still unclear.

### 3.1. Dynamic Foot Stimulation

It has been hypothesized that the body unloading and subsequent loss of support afferentation experienced during space flight induces a cascade of neuromotor alterations leading to neuromuscular dysfunction including loss of tonic muscle activation and subsequent post-flight postural and locomotor instability (Kozlovskaya *et al.* 2006; Kozlovskaya *et al.* 2007). Research has been conducted to examine the use of dynamic foot stimulation as a potential supplement to more traditional in-flight exercise countermeasures to mitigate neuromotor degradation associated with long-duration space flight. Several studies have shown that dynamic foot stimulation restores absent neuromuscular activation during space flight throughout the entire lower-limb musculature (Layne *et al.* 1998a). Mechanical stimulation of the feet was first applied on a Russian crewmember on the Salyut-6 space station using footwear with pneumatic bladders. It was reported that this stimulation preserved lower limb strength and locomotor function (Hernandez-Korwo *et al.* 1983).

Layne *et al.* (1998a) examined whether applying foot pressure using inflatable bladders inside boots during space flight could enhance the neuromuscular activation associated with posture perturbing rapid arm movements. The boots were worn during an 81-day mission for two crewmembers and 115 days for the two other crewmembers on the Mir space station. The crewmembers were required to perform rapid, unilateral shoulder flexions while free floating. The results showed that the application of foot pressure elicited lower limb and trunk activation typically observed in 1 g but that was not present without this stimulus in microgravity. Importantly, the lower-limb musculature response produced by foot stimulation was maintained through flight day 188 during a Mir mission indicating no habituation to the stimulus (Layne & Forth 2008). Another study examined mechano-stimulation of the soles support zones during exposure to 7 days of simulated microgravity conditions using the dry immersion technique that provides more gravitational unloading along the long axis of the body compared to bed rest. Foot pressure was applied to the heel and forefoot every day for 20 minutes. Subjects completed slow 10 minute pacing followed by 10 minutes of fast pace walking simulations. The results showed that electromyographic activities of leg extensors improved with the use of foot stimulation. In addition there was an increase in flexor muscle activity (Layne & Forth 2008).

Mechano-stimulation of the soles of the feet has been shown to improve postural equilibrium control and functional mobility. In a previous study subjects were asked to negotiate a complex obstacle course before and after 60 days of bed rest (Reschke *et al.* 2009). In this study bed rest subjects performed the Functional Mobility Test (FMT) which entailed

walking at a self-selected pace through an obstacle course set up on a base of medium density foam. Also, unique to this study was that daily foot massages were given to all bed rest subjects, after the first three subjects were completed to ameliorate the tenderness of the soles of feet. So the first three subjects tested did not receive any foot stimulation for the duration of the study. This enabled a comparison in performance between these two groups. Subjects in both groups showed a significant increase in their time to complete the course after bed rest. However, subjects who did not receive foot massage performed much worse after bed rest (94% increases in time) compared to those who did receive foot massage (27% increase in time). These data point to the importance of foot tactile and pressure input as a central component in the control of posture and locomotion.

A more recent study investigated the impact of space flight induced changes in the level of foot skin sensitivity on post-flight postural disequilibrium. Skin sensitivity of Shuttle astronauts was measured as vibration perception at the great toe, fifth metatarsal and heel. Both increased and decreased skin sensitivity was observed post-flight. Increased skin sensitivity was associated with a greater reduction in postural equilibrium control using computerized dynamic posturography (CDP) pointing to the importance of foot skin receptors in maintaining balance control and its role in post-flight postural disequilibrium (Lowrey *et al.* 2014).

In support of the observations above, stimulation of the plantar surface of hindlimb-suspended rats resulted in preservation of soleus muscle mass cross sectional area (Kyparos *et al.* 2005). These studies used a pneumatic cuff that rapidly inflated and deflated to provide dynamic stimulation to the soles. The rats in the experimental group received this foot stimulation for only 5.6% of the entire period they were suspended, therefore, this relatively short time period of exposure was sufficient to maintain muscle size despite the limb unloading. Therefore, restoring support-loading afferentation by providing foot tactile input can be used to prevent muscle atrophy associated with space flight.

### 3.2. Load Suits

Load suits are composed of adjustable elastic bands that produce tension over the chest, back, abdomen, side, and leg seams. The suits were first worn by the crews of the Soyuz-13 and Soyuz-14/Salyut-3. Although the load suits were considered "pleasant," illusions, headward fluid shifts, and symptoms of SMS were still present (Gurovskii *et al.* 1975; Vorob'ev *et al.* 1975).

New systems are currently being developed. For example, the Variable Vector Countermeasure Suit (V2Suit) uses inertial measurement units and control moment gyroscopes within miniaturized modules placed on body segments to provide a viscous resistance during movements against a specified direction of "down" (Duda *et al.* 2015). This suit could act as a countermeasure to the sensorimotor adaptation performance decrements during long-duration spaceflight, including post-flight recovery and rehabilitation. This type of countermeasure system also has Earth benefits, particularly in gait or movement stabilization and rehabilitation.

### 3.3. Pneumatic Devices

To reduce or prevent cephalad fluid shifts, the Soyuz-38 crew wore a pneumatic occlusion cuff on the hips. The cuff, worn for 20 to 30 minutes at -40 to -60 mmHg, reportedly decreased or eliminated dizziness, illusions, nausea, and the sensation of head pulsation (Matsnev *et al.* 1983; Gorgiladze & Bryanov 1989).

The neck pneumatic shock absorber (NPSA) device, a cap with rubber cords that provide a load to the cervical vertebrae and neck muscles, stretches the user's neck muscles to maintain an erect head position and to restrain any turning or tilting of the head (Matsnev *et al.* 1983). The NPSA was designed to be worn during working hours for the first 3 or 4 days of a mission. It was used on the Soyuz-T3, -49, -40, and T-7 spacecrafts as well as on the Salyut-6 and -7 orbital stations. Cosmonauts reported the NPSA to be effective in alleviating dizziness, illusions, discomfort, and nausea with no adverse effect on performance (Matveyev 1987). This was attributed to "normalization of the vestibulocervical reflex system". However, head movements, which are known to provoke SMS symptoms, were limited by this device.

### 3.4. Stroboscopic Goggles to Mitigate Motion Sickness

Motion sickness in the general population is a significant problem driven by increasingly sophisticated modes of transportation, visual displays, and virtual-reality environments. It is important to investigate nonpharmacological alternatives for the prevention of motion sickness for individuals who cannot tolerate the available anti-motion sickness drugs, or who are precluded from medication because of operational environments. Both NASA and the U.S. Army have been investigating stroboscopic vision as a way to provide a simple and easily managed treatment for motion sickness (Reschke *et al.* 2006). Specifically, a five-part study was designed to investigate the effect of stroboscopic vision (with either a strobe light or liquid crystal display [LCD] shutter glasses) on motion sickness while (1) using visual field reversal; (2) reading while riding in a car (with or without external vision present); (3) making large pitch head movements during the 0 g phase of parabolic flight; (4) exposed to rough seas in a small boat; and (5) seated and reading in the cabin area of a UH60 Black Hawk helicopter during provocative flight patterns. A total of 69 subjects participated in selected phases of the study. Fewer subjects suffered from motion sickness under stroboscopic conditions. Stroboscopic illumination prevents retinal slip, thereby treating motion sickness symptoms. Shutter glasses with a cycle frequency of 4 or 8 Hz and a short dwell (glasses clear) time (10–20 ms) are as effective as a strobe light, producing a useful adaptation during either self- or surround-motion without the penalty of using disabling MS drugs (Reschke *et al.* 2007b).

### 3.5. Tactile Spatial Awareness System

A recent joint ESA-NASA pre- and post-flight experiment was designed to examine both the physiological basis and operational implications for disorientation and tilt-translation disturbances in astronauts after short-duration space flights. Changes in eye movements and motion perception were investigated during independent tilt and translation motion profiles in eight crewmembers returning from Space Shuttle missions. Roll motion was provided by a variable-radius centrifuge, while pitch motion was provided by NASA's Tilt-Translation Sled, in

which the resultant gravitoinertial vector remains aligned with the body's longitudinal axis during tilt motion. Subjects were told to use a joystick to nullify tilt motion disturbances on these two devices. The stimuli consisted of random steps or sum-of-sinusoids.

Results showed that the ability to control tilt orientation was compromised following space flight, with an increased number of errors corresponding to changes in self-motion perception. However, the use of a tactile spatial awareness system (TSAS) improved manual control performance. During the closed-loop nulling task on both devices, small tactors placed around the torso vibrated according to the actual body tilt angle relative to gravity. Performance on the closed-loop tilt control task improved with the tactile display feedback of tilt orientation during both pre- and post-flight testing. In fact, with the TSAS, the performance during early post-flight tests was comparable to that without TSAS during the preflight tests (Clément et al. 2014).

## 3.6. Electrical Devices

### 3.6.1. Electroanalgesia

The use of weak electrical currents also has been explored to prevent or treat motion sickness. Electroanalgesia or electrotranquilization involves the use of two electrodes with one placed on the forehead and one on the mastoid process. Melnik et al. (1986) increased the current until the subject reported a sensation of warmth in the area of the electrodes; sessions lasted 30 to 60 minutes. Nekhayev et al. (1986) and Polyakov (1987) incorporated a pulsed current during sessions lasting an hour. Electroanalgesia did not increase resistance to experiment-induced motion sickness when sessions were performed before stressful motion. However, sessions conducted between two motion-stressor tests reduced or eliminated the residual symptoms from the first test and increased tolerance to the test performed after the electroanalgesia session. A second electroanalgesia session after the second motion-stressor test also improved recovery from symptoms induced by that test. No undesirable side effects were reported.

Ivanov & Snitko (1985) observed that motion sickness affected conductivity alongside standard acupuncture pathways regardless of symptom severity. Electro-acupuncture was used successfully by this group to treat seasickness. Others have found electrical acustimulation and acupressure to be effective in reducing vection-induced nausea (Hu et al. 1992, 1995). Acustimulation may work by enhancing the normal slow-wave myoelectrical activity of the stomach (Lin et al. 1997). Sub-threshold multichannel electrical stimulation of the antigravity cervical muscles also was reported to be promising as a countermeasure against motion sickness (Matveyev 1987).

Although electrical devices are reported to be effective in counteracting terrestrial motion sickness, they have not been tested in the space environment. Data obtained from in-flight questionnaires indicated that all the mechanical devices used in-flight improved how the cosmonauts felt and also led to the attenuation of illusions to some extent. Of these, the NPSA was reported to be the most effective. Sleep and the performance of demanding work tasks, which distracted the cosmonauts from the unpleasant sensations, also decreased symptoms of discomfort (Bryanov et al. 1986; Kornilova et al. 1995).

### 3.6.2. Galvanic Vestibular Stimulation

Galvanic Vestibular Stimulation (GVS) entails electrical stimulation to the vestibular labyrinth via surface electrodes placed over the mastoid bones that pass small currents that activate primary vestibular afferents. It has been used to stimulate the vestibular labyrinth artificially for laboratory studies of human vestibular cortex, spatial orientation, postural control and locomotion (Moore et al. 2011, 2015). GVS produces behavioral changes in balance function, gaze, head-trunk coordination and locomotor disturbances that are similar to those observed in post-flight astronauts (Moore et al. 2006). GVS has been validated in the Vertical Motion Simulator at NASA Ames during high-fidelity Shuttle landing simulations. When exposed to GVS, pilot subjects (including a veteran shuttle commander of 3 flights), experienced spatial disorientation and subsequent decrements in landing performance equivalent to that observed in actual Shuttle landings (Moore et al. 2011). The GVS analog accurately reproduces the effects of microgravity exposure on the central nervous system, and might be used to improve training of astronauts for future long-duration missions (Dilda et al. 2014). Dilda et al. have shown that subjects exhibit central adaptation phenomenon with repeated GVS exposure in a study of normal subjects for an extended period of up to 12 weeks (120 min of total exposure). During each trial subjects performed computerized dynamic posturography and eye movements were measured using digital video-oculography. Follow up tests were conducted 6 weeks and 6 months after the 12-week adaptation period. Postural performance was significantly impaired during GVS at first exposure, but recovered to baseline over a period of 7–8 weeks (70–80 min GVS exposure). This postural recovery was maintained 6 months after adaptation. In contrast, the roll vestibulo-ocular reflex response to GVS was not attenuated by repeated exposure. This suggests that GVS adaptation did not occur at the vestibular end-organs or involve changes in low-level (brainstem-mediated) vestibulo-ocular or vestibulo-spinal reflexes. Faced with unreliable vestibular input, the cerebellum reweighted sensory input to emphasize veridical extra-vestibular information, such as somatosensation, vision and visceral stretch receptors, to regain postural function. After a period of recovery subjects exhibited dual adaption and the ability to rapidly switch between the perturbed (GVS) and natural vestibular state for up to 6 months. In a follow up study (Moore et al. 2015) found that pre-adaptation to GVS is associated with enhanced sensorimotor performance in a flight simulator and asked to null the roll motion of a visual bar presented on a screen using a joystick compared to subjects who were not adapted to GVS. Thus GVS may be used as a training modality to enhance adaptability to aid recovery after space flight (Dilda et al. 2014; Moore et al. 2015).

### 3.6.3. Vestibular Stochastic Resonance

A general phenomenon of neural systems is that paradoxically if noise is added to neural sensory systems, their ability to detect sub-threshold signals improves, which is a mechanism termed Stochastic Resonance (SR). SR thus enables the enhanced detection of relevant sensory signals. SR can be thought of simply as "noise benefit" by increasing information transfer in the presence of non-zero level of noise (for reviews see (Collins et al. 2003; Moss et al. 2004; McDonnell and Abbott 2009; Aihara et al. 2010). SR has been observed in human hearing (Jaramillo and Wiesenfeld 1998; Zeng et al. 2000; Ward et al. 2002) and has been identified as

an important component in cochlear coding strategy (Morse and Evans, 1996). The presence of stochastic noise to sensory input has been shown to improve: visual contrast sensitivity and detection (Simonotto *et al.* 1997; Ward *et al.* 2002); the degree of association between the heart rate responses and weak periodic oscillatory variation in central venous pressure (Soma *et al.* 2003); letter recognition (Piana *et al.* 2000); perception of ambiguous figures (Riani and Simonotto 1994); and visual depth perception (Ditzinger *et al.* 2000). SR in tactile sensation has been demonstrated in the response to weak mechanical stimuli (Collins *et al.* 1996a; b; Collins *et al.* 1997; Ivey *et al.* 1998; Richardson *et al.* 1998). The application of mechanical noise to the feet has been shown to improve balance control through the reduction of sway in young and elderly subjects (Priplata *et al.* 2002; Priplata *et al.* 2003), in patients with diabetes and stroke (Priplata *et al.* 2006) and patients with functional ankle joint instabilities (Ross and Guskiewicz 2006; Ross *et al.* 2013). Similarly, balance improvement has been demonstrated with electrical noise applied to the back of the knee (Gravelle *et al.* 2002). Vibratory noise applied to the fingertip also enhanced balance performance based on SR phenomenon (Magalhaes and Kohn 2011). These same authors have also shown that the application of imperceptible electrical noise to the triceps surae during a seated task reduced force fluctuations in a force matching task of isometric plantar flexion force which were correlated to subsequent reductions in postural sway during quiet stance based on SR phenomenon (Magalhaes and Kohn 2012). There have been a few studies that showed the effectiveness of applying sub-sensory vibratory noise to the soles of the feet during over-ground walking comparing elderly population with young control subjects (Galica *et al.* 2009). In a follow-up study, this group also showed the effectiveness of applying sub-sensory vibratory noise to the soles of the feet during treadmill walking in a set of control subjects (Stephen *et al.* 2012). SR using white noise based electrical stimulation at imperceptible amplitudes (at or below peri-threshold levels) of the vestibular system, applied using surface electrodes on the mastoid, leads to significantly improved balance, and locomotor performance during periods of novel sensory challenges in normals and Parkinsonian Disease patients (Mulavara *et al.* 2011, 2015a, 2015b, Goel *et al*. 2015, Samoudhi *et al.* 2015).

The methodology of using sub-threshold electrical stimulation of the vestibular system or similar stimulation of the proprioceptive systems at the sole of the feet will help retain and enhance the use of vestibular or proprioceptive information in performance of specific functions. Studies in the literature have investigated the usefulness of SR in conjunction with traditional training paradigms to improve performance (Ross and Guskiewicz 2006; Ross 2007; Ross *et al.* 2007; Ross *et al.* 2013). These investigators have shown significant improvement in postural balance control aiding recovery when electrical or mechanical SR stimulation to the muscles across the ankle joints was given in conjunction with conventional coordination training compared to training alone (Ross and Guskiewicz 2006; Ross 2007; Ross *et al.* 2007; Ross *et al.* 2013). Therefore, in general an individualized sensorimotor training program in conjunction with SR designed to promote the use of multiple sensory modalities can enhance the ability to adapt postural control and walking stability when exposed to a novel discordant sensory environment in the astronaut population.

## 4. ARTIFICIAL GRAVITY

Sensorimotor performance, but also bone loss, muscle weakening, and cardiovascular deconditioning, among other deficits, are all known deconditioning due to microgravity. The longer the flight duration, the more serious the health consequences become (Clément 2011). The current countermeasures on board the ISS (exercise, pharmaceutics, food complements) address each of these physiological systems in a piece-meal fashion. Artificial gravity, i.e., a sustained centripetal acceleration generated by centrifugation, represents a novel and integrated approach to addressing the detrimental effects of reduced gravity on the human body (Clément & Bukley 2007). All body systems are challenged simultaneously by its application, not simply one physiological system at a time. In addition, artificial gravity is an improvement upon the current ISS countermeasures as it addresses the root causes of the deconditioning phenomenon instead of treating its end-effects system-by-system as the current countermeasures do.

Recently, a special focus of concern is the deficit in vision acuity in astronauts on board the ISS, which is hypothesized to be caused by weightlessness-induced fluid shifts to the upper body leading to intracranial hypertension (Mader *et al.* 2011). If this hypothesis is confirmed, it could be an impediment for future long-duration deep space missions. Thus an effective countermeasure against these effects will be required. Because it enables re-establishing g-induced hydrostatic gradients, centrifugation might be the most efficient countermeasure.

Generating centrifugal force equivalent to the gravitational force on Earth during long-duration exploration missions can be obtained by rotating the entire spacecraft. However, this solution is costly in terms of power and mass, and it creates issues with navigation and control, communication, and docking. Another, more affordable solution, is to rotate only one part of the spacecraft, or to utilize an on-board human centrifuge.

To help inform the final decision on whether to conduct continuous spin of the whole space vehicle or to intermittently expose the crewmember to short-radius centrifugation, the limits of human adaptation in a rotating environment must be revisited. We need to identify the acceptable and/or optimal ranges for radius and rotation rate to avoid unacceptable crew health and performance consequences (Lackner & DiZio 2005a; Arya *et al.* 2007; Fong *et al.* 2007; Reinertson *et al.* 2007; Warren *et al.* 2007; Symons *et al.* 2009; Zwart *et al.* 2009). For intermittent applications, we need to identify what level, duration, frequency, and time of day of exposure to artificial gravity are optimal (Young *et al.* 2007). We also need to investigate the physiological responses to transitions between artificial gravity, microgravity, and Moon or Mars gravity because such studies would be useful in assessing whether dual adaptation to a rotating and a non-rotating environment is possible (Lackner & DiZio 2003).

NASA and other space agencies are working on a global research program on artificial gravity that would leverage the facilities available around the world (e.g., short- and long-radius centrifuges, slow rotating rooms, bed rest/dry immersion facilities, suspension systems, etc.) and integrate studies on human, animal, and cell models. Standardization of measures performed before and after each artificial gravity intervention will allow for more compatible

assessment across various studies. The biomedical measurements will focus on countermeasure validation, medical events, and subject acceptance and comfort.

Regarding sensorimotor performance, artificial gravity projects that could be performed in the near future include the following: (a) test gravity level values along Gz within the range from microgravity to 1 g, using the methods described above, to reasonably reach conclusions on the threshold, optimal stimulus-response, and saturation for the effects of centrifugation on sensorimotor performance; (b) test the effects of gravity levels higher than 1 G to assess whether increasing the intensity of the Gz stimulus actually reduces the time of exposure needed; (c) compare whether exposure to centrifugation for intermittent, short periods of time in one or multiple sessions is as beneficial as continuous exposure to Earth's gravity; (d) investigate whether Gz centrifugation reduces intracranial pressure and possibly mitigates the visual impairment due to intracranial pressure (VIIP) syndrome; (e) assess whether centrifugation can possibly mitigate post-flight decrease in performance by studying the effect of centrifugation on cognitive and functional tasks; and (f) assess the effects of gravity gradient on spatial orientation by comparing the responses in subjects placed at various distances from the axis of rotation on a long radius centrifuge (Clément *et al.* 2015b).

## VI. COMPUTER-BASED MODELING AND SIMULATION

While there are few robust ground-based models available for experimental investigations of the impacts of space flight on a crewmember's mobility and ability to maintain control of vehicles and complex systems, many computer-based models of the vestibular system and sensorimotor 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

### 1. MODELS OF VESTIBULAR FUNCTION AND SPATIAL ORIENTATION

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 $\omega$ is the component of head angular velocity in the canal plane, $K_i$ is mid frequency gain, $K_r$ is high frequency gain , $\tau_d$ and $\tau_c$ are the time constants of endolymph flow drag development and cupula-endolymph return (Groen 1957; Oman *et al.* 1987), and $\tau_a$ is a time constant describing neural adaptation (Young *et al.* 1969).

Young *et al.* (1967) 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 (1969; Young *et al.* 1973; Young *et al.* 1984) noted that laws of physics dictate that the body's graviceptors respond to the net gravito-inertial specific force (**f** = **g** − **a**), the physical quantity tracked by a pendulum or measured by a linear accelerometer (where **a** = linear acceleration vector and **g** = gravitational acceleration vector).  A variety of different orientations and accelerations can cause in 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 (**ĝ**) and subtracting off the graviceptor cue vector (**â** = **ĝ** - **f**). The direction of down, **ĝ** is estimated at low frequencies based on the average direction of graviceptor cues, **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 **ĝ** 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 (Borak *et al.* 1979), 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.* (1979), Robinson (1981), and Merfeld *et al.* (1993) 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 (Merfeld & Zupan 2002) 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.

## 2. 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" (McRuer 1972), 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 (Young 1967; Shirley & Young 1968). 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 (Young *et al.* 1973).

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 (Baron 1969) 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 (Curry *et al.* 1976; Baron 1983).

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 (Ashkenas *et al.* 1983). 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 (McRuer 1972). 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 (Smith & Edwards 1980). 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.

Landing on a planetary body requires a number of operational tasks including identification of an appropriate location that is level and free of hazards while maintaining a stable controlled descent to the surface. Various sensorimotor challenges may interfere with crewmembers' performance. These include the astronauts' first exposure to partial gravity following microgravity adaptation, the unique vehicle motions experienced on decent, and dust blowback from the descent engine thruster that may obscure vision. Models of human spatial orientation perception have been developed that can be used to predict the potential for disorientation in partial gravity environments (Clark *et al.* 2015). These models predict that spatial misperceptions are likely to occur during landings in partial gravity environments, particularly with limited or incomplete visual cues. For example a powered descent acceleration profile creates the misperception that the landing vehicle is upright, even when the vehicle has a large pitch or roll angle. When full visual information is provided these perceptual illusions are largely suppressed, however, dust blowback during landing may obscure visual cues out the window

and exacerbate spatial disorientation. These model predictions have been validated empirically using the NASA Ames Vertical Motion Simulator in which subjects self-reported their perceptions of vehicle motions during lunar-landing-like motions (Clark *et al.* 2014). Current research is focused on development of advanced display systems that could be implemented as countermeasures for landing spatial disorientation that include enhanced situation awareness displays and synthetic terrain displays that may help reduce potential landing misperceptions.

## VII.  RISK IN CONTEXT OF EXPLORATION MISSION OPERATIONAL SCENARIOS

### 1.  SENSORIMOTOR STANDARD

A sensorimotor standard has been drafted (NASA Standard 3001) for exploration class missions: "*Pre-flight sensorimotor functioning shall be assessed and be within normal values for age and sex of the astronaut population. In In-flight Fitness-for-Duty standards shall be guided by the nature of mission-associated high-risk activities. In-flight Fitness-for-Duty standards shall be assessed using metrics that are task specific. Sensorimotor performance limits for each metric shall be operationally defined. Countermeasures shall maintain function within performance limits. Post-flight reconditioning shall be monitored and aimed at returning to baseline sensorimotor function.*" However, operational performance limits related to mobility (e.g., emergency egress), 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.

The very first astronaut candidates underwent rigorous selection tests, including neurological tests, but NASA conducted little screening for vestibular or sensorimotor problems in subsequent groups of new astronauts, including those in the Space Shuttle program. As evidence evolved from early space programs through the Shuttle missions, sensorimotor and CNS problems began to become prevalent medical findings. Current medical history and exams for astronaut selection include: (a) no history of serious ongoing neurological disease, (b) examination by a neurologist, and (c) magnetic resonance imaging of the brain and magnetic resonance angiography of the head.

Abnormalities detected by these methods help to screen out some asymptomatic individuals, some of whom have potentially serious problems. NASA had already required the use of electroencephalography as a part of the selection process before instituting these additional rigorous neurological examinations. Attempts were made historically to use susceptibility to motion sickness, abnormal visual-vestibular function, and postural problems to screen out candidates. Much of this testing, performed by in-house laboratories at the NASA Johnson Space Center, was seldom weighted highly, primarily because researchers in the Neurosciences Laboratories were hesitant to recommend serious limits based on standards that did not reflect operational requirements.

The high degree of variability across crewmembers in terms of the severity of neurological symptoms, given the current knowledge base, suggests that medical selection and retention standards could be quite effective in minimizing the operational impacts of sensorimotor adaptation. However, the lack of validated assessment tools for predicting sensorimotor adaptation, or an individual's inability to adapt, has hindered the development of relevant selection standards. The capability for clinical diagnosis of vestibular disorders greatly advanced during the Space Shuttle era from direct spin-offs of Shuttle projects (e.g., postural testing, eye measurement technology, etc.) (Reschke *et al.* 2013). Although selection and retention standards for sensorimotor function have remained limited to neurological screenings of reflex

functions consistent with standard aviator flight physical examinations, extensive selection standards are now in place for vision, audition, and other sensory functions.

Flight rules have been used to minimize the operational consequences of vestibular and sensorimotor changes associated with microgravity. These rules primarily limited crew activities after G-transitions, particularly during the early days of flight, to allow the crew to adapt to SMS. Examples of rules are prohibition of extravehicular activities until the third day on-orbit because of concerns related to emesis in the spacesuits, and restriction of driving or flying until the third day after short-duration flights. When Shuttle flights resumed after the loss of Space Shuttle *Columbia*, computerized dynamic posturography testing was implemented as an aid for the return-to-duty assessment to supplement preflight and post-flight neurological examinations.

## 2. 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 sensorimotor adaptation to 0 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.

## 3. RISKS DURING VEHICLE EGRESS AND EXTRAVEHICULAR ACTIVITIES

Ensuring that crewmembers are able to egress the vehicle in the event an emergency occurs during the post-landing timeframe is essential to allowing them to survive or avoid serious injury during such an event. The crewmembers should also be able to function in 1-g environment in case of return to Earth, or in a 1/6-g or 3/8-g environment in case of lunar or Mars landing. Factors that affect egress in a timely manner include (a) visually determining hazards outside the vehicle, such as the presence of fire or debris; (b) having a hatch that can be operable by a single crewmember without the use of tools; and (c) having a egress path that allow egress of all occupants in a timely manner. Determining if it is safe to egress the vehicle and having an egress path requires good situation awareness, spatial orientation, and mental representation of space. Opening the hatch, egressing the vehicle, and walking in enough time

to protect from post-landing hazards may be compromised if crewmembers are incapacitated or in a deconditioned state. Orion and other commercial vehicles are currently designed for a parachuted landing on water after long-duration missions. In these water landing scenarios, the interaction between the adapted microgravity sensorimotor state and the prevailing unstable support surface induced by various sea state conditions will increase the risk associated with an emergency egress situation.

During Expedition 6 to the ISS, a series of unplanned events serendipitously created an analog mission for a trip to and landing on Mars. A spacecraft malfunction causing a ballistic entry which displaced the landing site about 475 kilometers off course resulting in about a 5 hour delay for arrival of the ground support team. This gave the crew an opportunity to perform spacecraft safing, egress, and set up survival gear without any outside help (Pettit 2010). The crew performed spacecraft safing, involving reading procedures, flipping switches, and pushing buttons on the control panel to power down unneeded equipment so that battery life for radio operations can be extended. Since the Soyuz capsule ended on its side, these operations were done from a position of being strapped into a seat fixed on a slanted ceiling. The crew opened the hatch, unstrapped, and crawled out. Following egress, they deployed the survival gear that was stowed in numerous small bundles throughout the spacecraft. Included were warm woollen cloths, food, water, a medical kit, a portable radio, and a signalling kit.

One crewmember reported that "performing these basic survival tasks was not easy. Moving was provocative. […] Walking was labored but was done as needed shortly after landing. I had trouble walking but could crawl. […] There were no systemic aches or pains associated with movement. We had good muscle strength. […] My limbs felt heavy because my brain was not yet compensating for their weight. [..] Upon returning, the brain had not yet kicked in this compensation which takes about 10 to 15 hours. Slow and deliberate motions were readily made with sufficient motor control to connect electrical wire harnesses, antennas, cycle switches on control panels, and shoot a shotgun pistol. Motor control for operating the spacecraft mechanisms and survival gear was not a problem. However, fast coordinated movement was not possible for me." (Pettit 2010). In addition, this crewmember recommended that "a well-designed [Mars] mission should have minimal demands on the crew after landing, giving them a few days for adaptation before engaging in significant operational tasks."

## 4. 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 sensorimotor 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 sensorimotor 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 0-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.

## 5.  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 0-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 0 g during return transit are unknown, and may well lead to an unacceptable range.

## 6.  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.

## 7.  RISKS DURING NEAR-TERM MISSIONS

The current sensorimotor risk is now high in priority given the prospect of long-duration Mars missions and planned water landings following long-duration ISS missions. There is significant evidence showing sensorimotor alteration after as little as a few weeks of exposure to space flight environments, and that severity increases with increasing exposure time. 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 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 sensorimotor adaptation risks, can be ignored. The near misses reported above provide evidence in this regard. Given the reentry profiles and cross-coupled Coriolis effects induced by the drogue parachutes under nominal Orion re-entry/descent/landing scenarios it will likely be a much more difficult sensorimotor environment than for Shuttle landings. Finally, the proper resolution of automation-human control authority decisions requires an objective and quantitative understanding of sensorimotor 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.

## VIII.   GAPS

The authors, representing the sensorimotor (SM) discipline team, have identified the series of knowledge and mitigation gaps listed below. Each of them must be filled before this risk can be fully assessed and/or mitigated.

**SM2.1** – Determine the changes in sensorimotor function over the course of a mission and during recovery after landing.

**SM2.2** – Determine the effects of long-duration space flight on sensorimotor function over a crewmember's lifetime.

**SM6.1** – Determine if sensorimotor dysfunction during and after long-duration space flight affects ability to control spacecraft and associated system.

**SM7.1** – Determine if there are decrements in performance on functional tasks after long-duration space flight. Determine how changes in physiological function, exercise activity, and/or clinical data account for these decrements.

**SM24** – Determine if the individual capacity to produce adaptive change (rate and extent) in sensorimotor function to transitions in gravitational environments can be predicted with preflight tests of sensorimotor adaptability.

**SM26** – Determine if exposure to long-duration space flight leads to neural structural alterations and if this remodeling impacts cognitive and functional performance.

**SM27** – Determine the most optimal pharmacological and sensorimotor countermeasure combination that reduces Space Motion Sickness (SMS) while minimizing side effect.

**SM28** – Develop a sensorimotor countermeasure system integrated with current exercise modalities to mitigate performance decrements during and after space flight.

## IX. CONCLUSION

A large body of sensorimotor research data obtained from space flight experiments over the past half-century demonstrates significant decrements in oculomotor control, eye-hand coordination, spatial orientation, posture\locomotor control 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 circa 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 sensorimotor (and other) changes on crew mobility and 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 sensorimotor changes to date, the impacts of new mission and vehicle designs may offset some of benefits.

Forward work in this area must account for the multi-factorial nature of the problem. While sensorimotor 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.

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# XI. LIST OF ACRONYMS

| | |
|---|---|
| AFT | Autogenic Feedback System |
| ARED | Advanced Resistive Exercise Device |
| CDP | Computerized Dynamic Posturography |
| CEVIS | Cycle Ergometer with Vibration Isolation System |
| CFIT | Controlled Flight Into Terrain |
| CMD | Commander |
| CNS | Central Nervous System |
| COLBERT | Combined Operational Load Bearing External Resistance Treadmill |
| Dec | Decrease |
| DIS | Document Index System |
| DOF | Degree of Freedom |
| DOME | Device for Orientation and Motion Environments |
| DOUG | Dynamic Onboard Ubiquitous Graphics |
| DVA | Dynamic Visual Acuity |
| EAFB | Edwards Air Force Base |
| ECV | Exploration Class Vehicle |
| EOM | Effective Oculomotor Range |
| EQ | Equilibrium |
| EVA | Extra-Vehicular Activity |
| FMT | Functional Mobility Test |
| FTT | Functional Task Test |
| GCA | Ground Control Assist |
| GCR | Galactic Cosmic Rays |
| GIA | Gravitoinertial Acceleration |
| GPWS | Ground Proximity Warning System |
| GVS | Galvanic Vestibular Stimulation |
| HAC | Heading Alignment Cone |
| HUD | Head Up Display |
| HRP | Human Research Program |
| IBMP | Russian Institute of Biomedical Problems |
| IM | Intramuscular |
| Inc | Increase |
| iRED | interim Resistive Exercise Device |
| ISS | International Space Station |
| KSC | Kennedy Space Center |
| LCD | Liquid Crystal Display |
| LEE | Latching End Effector |
| LM | Apollo Lunar Module |
| MCC | Mission Control Center |
| MS | Mission Specialist |
| MSBLS | Microwave Scanner Beam Landing System |
| MT | Mobile Transporter |

| | |
|---|---|
| NPSA | Neck Pneumatic Shock Absorber |
| NTS | Nucleus tractus Solitarius |
| NTSB | National Transportation Safety Board |
| NVA | Near Visual Acuity |
| OCR | Ocular Counterrolling |
| OKN | Optokinetic Nystagmus |
| ONTO | Oxygen/Nitrogen tank |
| OTTR | Otolith Tilt-Translation Reinterpretation |
| OVAR | Off Vertical Axis Rotation |
| PAPI | Precision Approach Path Indicator |
| PFMS | Post-Flight Motion Sickness |
| PIO | Pilot Induced Oscillation |
| PLT | Pilot |
| PS | Payload Specialist |
| PSOI | Post-Spaceflight Orthostatic Intolerance |
| ROTTR | Rotation Otolith Tilt-Translation Reinterpretation |
| SA | Sensorimotor Adaptability |
| SD | Spatial Disorientation |
| SFRM | Space Flight Resource Management |
| SM | Sensorimotor |
| SMS | Space Motion Sickness |
| SPE | Solar Particle Event |
| SR | Stochastic Resonance |
| SSRMS | Space Station Remote Manipulator System |
| STA | Shuttle Training Aircraft |
| STS | Space Transportation System (Space Shuttle) |
| TACAN | Tactical Air Navigation |
| TAEM | Terminal Area Energy Management |
| TAWS | Terrain Awareness and Warning System |
| TCC | Time to Complete the Course |
| TSAS | Tactile Spatial Awareness System |
| TTD | Tilt-Translation Device |
| TVIS | Treadmill Vibration Isolation System |
| UHF | Ultra High Frequency |
| VEMP | Vestibular Evoked Myogenic Potentials |
| VIIP | Vision Impairment and Intercranial Pressure |
| VOR | Vestibulo-Ocular Reflex |
| VRI | Visual Reorientation Illusion |
| VRT | Vestibular Rehabilitation Therapy |

## XII. APPENDIX A: SHUTTLE LANDING PERFORMANCE

**Authors: Millard F. Reschke, Deborah L. Harm, William H. Paloski, Jacob J. Bloomberg, Scott J. Wood**

**Shuttle Landing Performance**

Control of vehicles, and other complex mechanical motion systems, is a high-level integrative function of the central nervous system (CNS) that requires good visual acuity, eye-hand coordination, spatial (and, in some cases, geographic) orientation perception, and cognitive function. Existing evidence from space flight research (Paloski *et al.*, 2008; Clément and Reschke 2008; Reschke *et al.*, 2007) demonstrates that the function of each of these systems is altered by removing (and subsequently by reintroducing) a fundamental orientation reference (gravity), 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 system depends on crew experience and mission-related factors.

There is only limited operational evidence that alterations in the gravitoinertial force environment will 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.

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, more than 500 sensorimotor experiments have been performed during and/or after space flight missions since 1959 (reviewed by Reschke *et al.* 2007). While not all of these experiments were directly relevant to the question of vehicle/complex system control, many provide insight into changes in aspects of sensory-motor control that might have a bearing on the physiological subsystems underlying this high-level integrated function.

**Evidence Obtained from Observation, Analysis, and/or First Hand Reports of 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, existing operational data has been previously inaccessible to life sciences researchers. Recent programmatic changes have putatively improved access to both data and experts to help with interpretation. However, a real understanding of the factors involved in manual control will come with dedicated investigations that specifically address the problem.

**Landing the Space Shuttle**

The space shuttle landing process begins on the opposite side of the world from the primary landing strip with a deorbit burn approximately one hour before touchdown. If the primary runway is located at the Kennedy Space Center (KSC) reentry begins over the Indian Ocean off of the western coast of Australia. Thirty minutes before landing the orbiter enters the Earth's atmosphere at an altitude of 121,920 m and flies across the Pacific Ocean, the Baja Peninsula, Mexico, southern Texas, and out over the Gulf of Mexico to the west coast of Florida. Adapted to a weightless environment, the entry process places an inertial load on the shuttle crew that lasts for a minimum of 5 min and ranges from 1.2 to 1.6-g with the summed gravitoinertial acceleration (GIA) vectors (gravity and centripetal) located primarily through the Z-axis.

Within approximately 5.5 min prior to landing, the shuttle is traveling at 2,735 km/hr (1,700 mph) at an altitude of 25,338 m, and the crew is conserving the falling spacecraft's energy needed to reach the landing strip (Terminal Area Energy Management or TAEM). The final approach into KSC begins with runway alignment (first waypoint in the final landing process). As illustrated in Figure 1, runway alignment is accomplished by flying the shuttle around one of two imaginary cones (heading alignment cones or HAC) about 11 km from the end of the runway (threshold). Depending on the runway, approach and available energy, flight around the HAC (from 0° to 360°) can be low energy (shallow bank angle) or high energy (higher bank angle). A high energy HAC can peak at close to 2.0-g and present potential manual control problems to the weightless adapted commander and pilot.
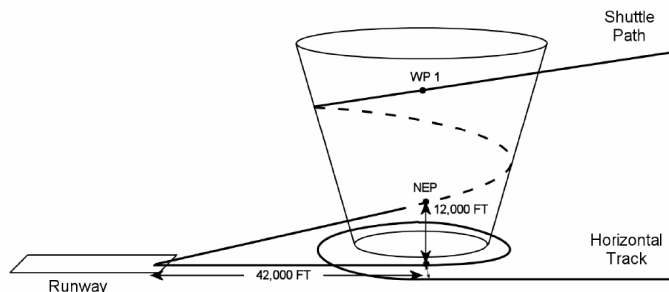


*Figure 1. Path of the space shuttle into KSC.*

The shuttle leaves the HAC at what is called the runway entry point, descending on a 20-22° glide slope within 12 km (7.5 mi) to the runway threshold (Figure 2) at 682 km/h (424 mph). In addition to the head-up display (HUD), which most commanders we have interviewed

indicate is used primarily on roll out to the final approach, there are other landing aids that can help guide the shuttle to a safe landing. These include: (1) the Tactical Air Navigation (TACAN) system that provides range and bearing, (2) the Microwave Scanner Beam Landing System (MSBLS) that provides precise close-in information on slant range, azimuth and elevation, (3) the Precision Approach Path Indicator (PAPI) lights that show the commanders if they are on the correct outer glide slope, and (4) the Ball-Bar Light system that provides a visual reference to the inner glide slope and height off of the runway surface (e.g. high or low).
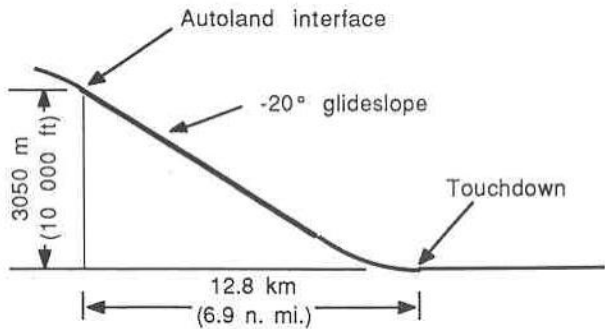
*Figure 2. Final approach of the shuttle.*

At 17 sec to touchdown with the spacecraft 1,079 m from the runway threshold and traveling at approximately 496 km/h (308 mph) the commander completes a pre-flare maneuver bringing the shuttle 1.5° nose-up on a 1.5° glide slope. At 14 sec to touchdown the wheels are lowered (335 m altitude - 100 ft) at 496 km/h (270 mph). Touchdown occurs 689 m (2,270 ft) down range from the runway threshold with an air speed of 346 km/h (215 mph). The KSC runway is 4,572 m (15,000 ft) long and 91.4 m (300 ft) wide while the alternate orbiter landing site at Edwards Air Force Base (EAFB) has several dry lake bed runways and one hard surface runway. The longest strip at EAFB is 12 km long (7.5 miles). There are a number of parameters that can be traded off to achieve a safe landing, some specific values that are highly desirable and others that are mandatory to avoid potential loss of the spacecraft during the landing process. The preferred touchdown should occur downrange on the runway from 2200-2700 ft. Less than 1000 ft is considered dangerous and more than 5000 ft risks brake and tire problems. Crossrange the spacecraft should touch down within ± 12 ft (optimal) of the runway center, but keeping the vehicle between ± 50 ft is acceptable. Optimal touchdown airspeed ranges between 210 kts and 185 kts depending on vehicle weight. Optimal sink rate is between 2 and 3 fps, however anything lower than 4 fps is acceptable. A pitch attitude between 8-10 deg is optimal, not to exceed 14 deg (14.6 deg will result in tail-scrape) at touchdown.

## Shuttle Entry and Landing Spatial Disorientation

Despite recent (relative to launch), intensive training for all shuttle commanders and pilots, all shuttle landings have not been performed as well as desired, perhaps in part as a result the loss of situational awareness and out right spatial disorientation. Shuttle entry and landing spatial disorientation (SD) differs from aviation SD, at least in terms of prevalence. Almost every instrument rated aircraft pilot has experienced SD, but episodes occur relatively infrequently in ordinary flying. In contrast, stimuli capable of producing SD are present during every Shuttle

landing. The issue is whether the astronaut commander can successfully fly through it. Tilt Gain and OTTR illusions do not occur in astronauts practicing approaches in the Shuttle Training Aircraft (STA), so their actual experiences with these illusions occurs 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) and to land the STA thousands of times prior to the actual shuttle landing. Fortunately, on the 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.
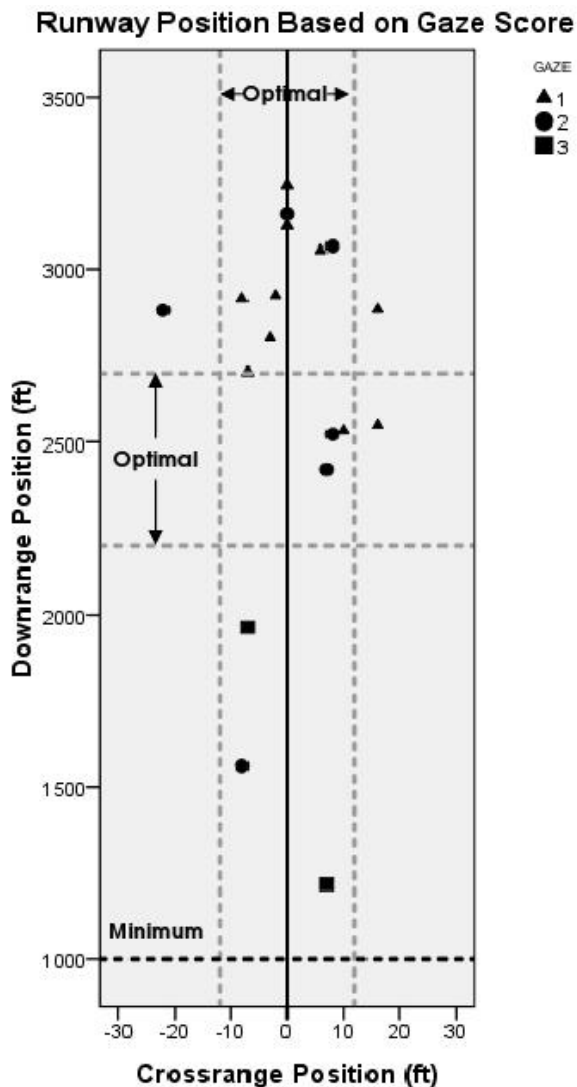


*Figure 3. This plot shows a runway with the minimum allowable touchdown point noted at 1000 ft, and the optimal range between 2200 and 2700 ft. Severity of the gaze problem is indicated by the symbols: Triangle = minimal, circle denotes a moderate gaze problem, and squares indicate severe gaze difficulty as judged by the attending flight surgeons.*

Beginning with STS-80, returning Shuttle crews have been examined by flight surgeons for neurologic dysfunction within several hours of landing. Commanders were scored for subjective symptoms, coordination, and functional motor performance. McCluskey *et al.* (2001) analyzed

data from nine missions, and noted trends, such as an apparent correlation between down range touchdown, sink rate and difficulty arising from a chair without using the arms. Generally scores indicative of neurovestibular dysfunction correlated with flying a lower approach and landing shorter or longer, faster, and harder. When plotted as a function of generalized gaze problems observed by the flight surgeons, there were only four landings within the optimal range on the runway. When gaze was judged as severely affected the landings were clearly short of the desired touchdown point (Figure 3). These observations suggest that further analysis of Shuttle landing performance is warranted.

Both optimal and less than optimal landing are charted in Figure 4. This figure shows the landing of 58 shuttle flights for which we could obtain accurate speed of the vehicle over the threshold. It is clear that only a few of the landing occur within the optimal touchdown area, with many landing short of this area, but more importantly, plotting the landing in this fashion shows the trade-offs that can be used to safely put the shuttle on the ground.
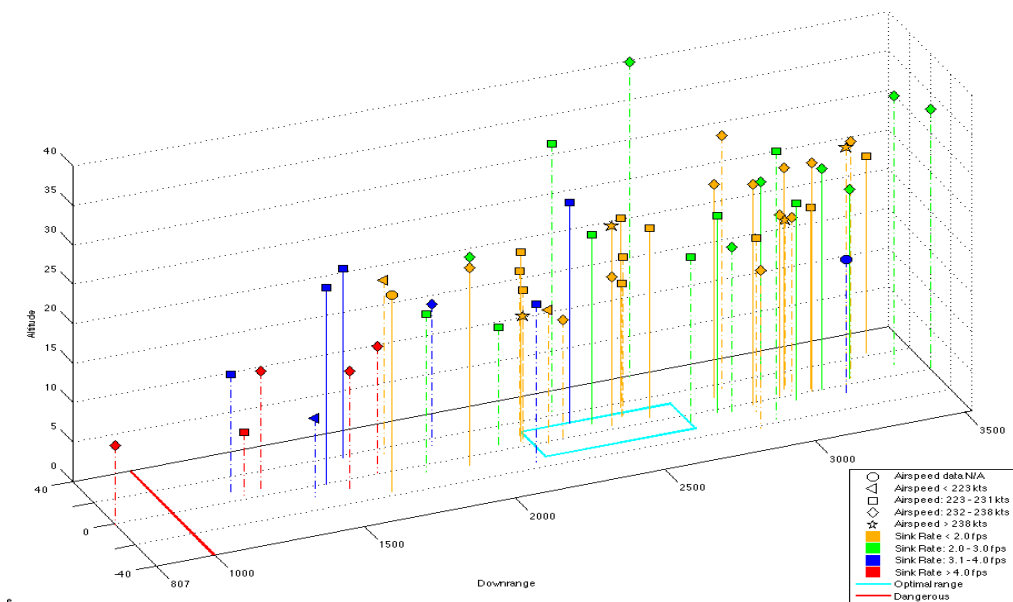


*Figure 4. 3-D plot of 58 shuttle landings, superimposed on the landing strip, showing the touchdown point (crossrange = Y, downrange = X and altitude over the runway threshold = Z) associated with each landing. Sink rates are indicated by specific colors (yellow = <2 fps, green = 2 to 3 fps, blue = 3.1 – 4 fps and red indicates sink rates greater than 4 fps). Airspeed velocities over the runway threshold are shown as symbols (Circle indicates no data is available, left facing triangle = < 223 kts, square = 223 – 231 kts, diamond = 232– 238 kts and the star = velocities > 238 kts. The dashed and solid lines connecting the pinheads to the runway show altitude (solid = optimal height off of the runway surface and dashed = altitudes either higher or lower than optimal). The blue square represents the optimal runway touchdown area, and the red line on the Z-axis shows touchdown clearly short of the optimal downrange distance required for a safe landing.*

When additional flights are added (where we do not have threshold velocity, but do have touchdown velocity) it can be seen that several flights have been extremely close to the runway threshold, and at least one flight landed (at EAFB) short of the runway threshold (Figure 5). All of the yellow symbols have less than the optimal sink rates. However, touchdown velocity for these flights suggests that there was (in most cases) energy available for successful downrange landings. The data we have from some of these short landing has indicated that there may have been some difficulty while flying the HAC, including significant spatial disorientation. Furthermore, several commanders have indicated that they believed they were higher off the runway surface than they actually were, and that the spatial disorientation may have involved issues with their perception of speed (motion parallax).

Most commanders interviewed have indicated that perceptually it is not possible to accurately judge sink rates. This could be related to not only motion parallax, but to the difficulty most have in accurately determining vertical position when translated in the Z-axis parallel to the gravitational vector. In any case, of all the landings between STS-1 and STS-108, the Shuttle crossed the runway threshold abnormally low 20 times, and vehicle speeds at touchdown were fast or slow of the targeted value 23 times (10 exceeded flight rules and two exceeded the tire speed limit). Seven landings touched down abnormally long or short, and 13 had high touchdown sink rates, with three exceeding the 5 ft/s structural limit.

Regardless of the commanders ability to land the shuttle following stays of various length in a weightless environment, there are other critical aspects of vehicular control that relate to Lunar landing, docking while on orbit and control of the remote arm found on both the shuttle and International Space Station. In all of these situations eye-head-hand coordination, perception of speed (sink rates and closing velocities), motion parallax in a visually barren environment, and vection or perception of self/surround motion could be critical components in the control of a spacecraft, lunar rover or remote 3-D manipulation system.
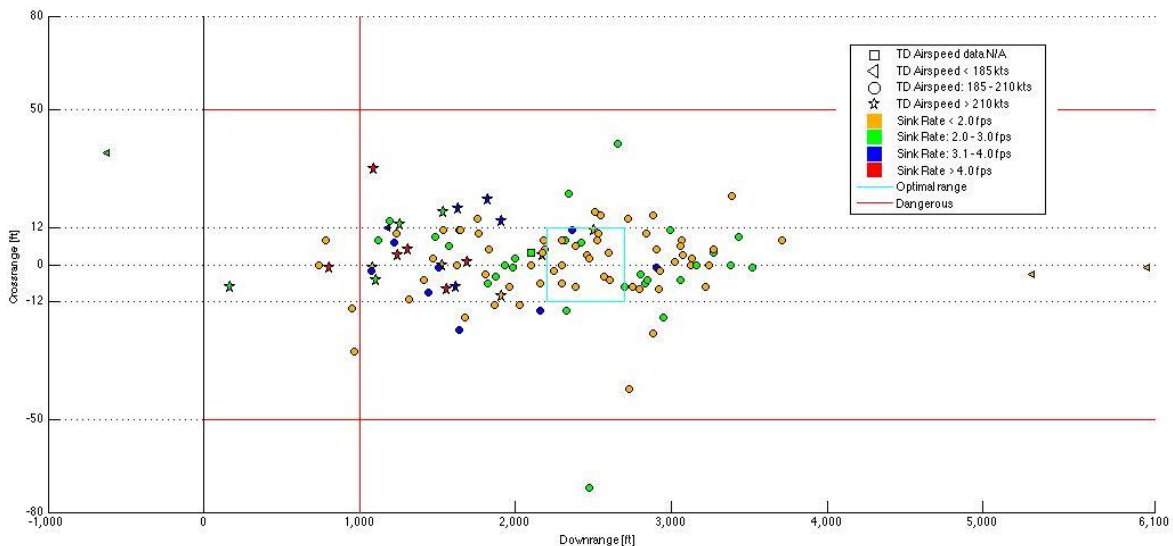


*Figure 5. Sink rate, roll angle, and y-position at touchdown are a result of atmospheric conditions and how well the commander flies the vehicle.*

The following graphs summarize shuttle landing performance data across several landing parameters including:

**Touchdown Downrange Position (Distance from the Threshold)**
Nominal range from 2200-2700 ft. NOTE: Pilots have mentioned that 1000 ft should be the minimum as it is dangerously close.

**Touchdown Sink Rate (Altitude rate)**
Vertical Speed at touchdown; Nominal = -2 to -3 fps, not to exceed -4 fps.

**Altitude over Threshold**
Height over runway start; Nominal = 23-29 ft.

**Touchdown Groundspeed**
High groundspeed at touchdown results in excessive tire wear and possibly tire failure. Tires are approved up to 225 kts.

**Touchdown Pitch Attitude**
Nose-up pitch at landing. Nominal = 8-10°, not to exceed 14°.
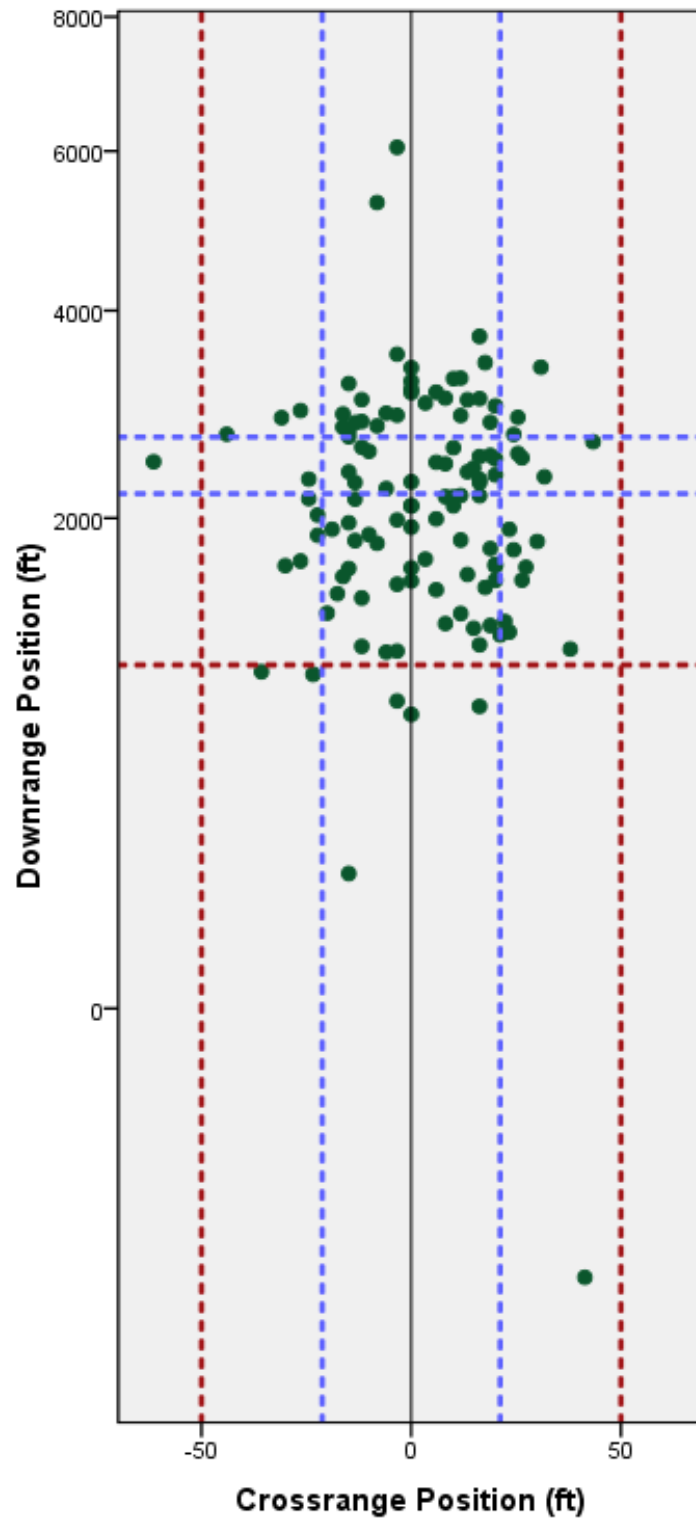
**Touchdown Crossrange**
Distance from centerline (Y position) on runway position; nominal range is $0 \pm 12$.

**Touchdown Equivalent Airspeed**
Lightweight vehicles: 195 KEAS (+5, -10)
Heavyweight vehicles: 205 KEAS (+5, -10)

**Touchdown Position on Runway**

**Downrange Position**

The approach and landing trajectory is designed to nominally touchdown the orbiter 2500 ft downrange at a safe speed and small altitude rate. Most runways also have painted markers at the nominal 2500-ft touchdown location to give the pilot's a downrange point of reference.
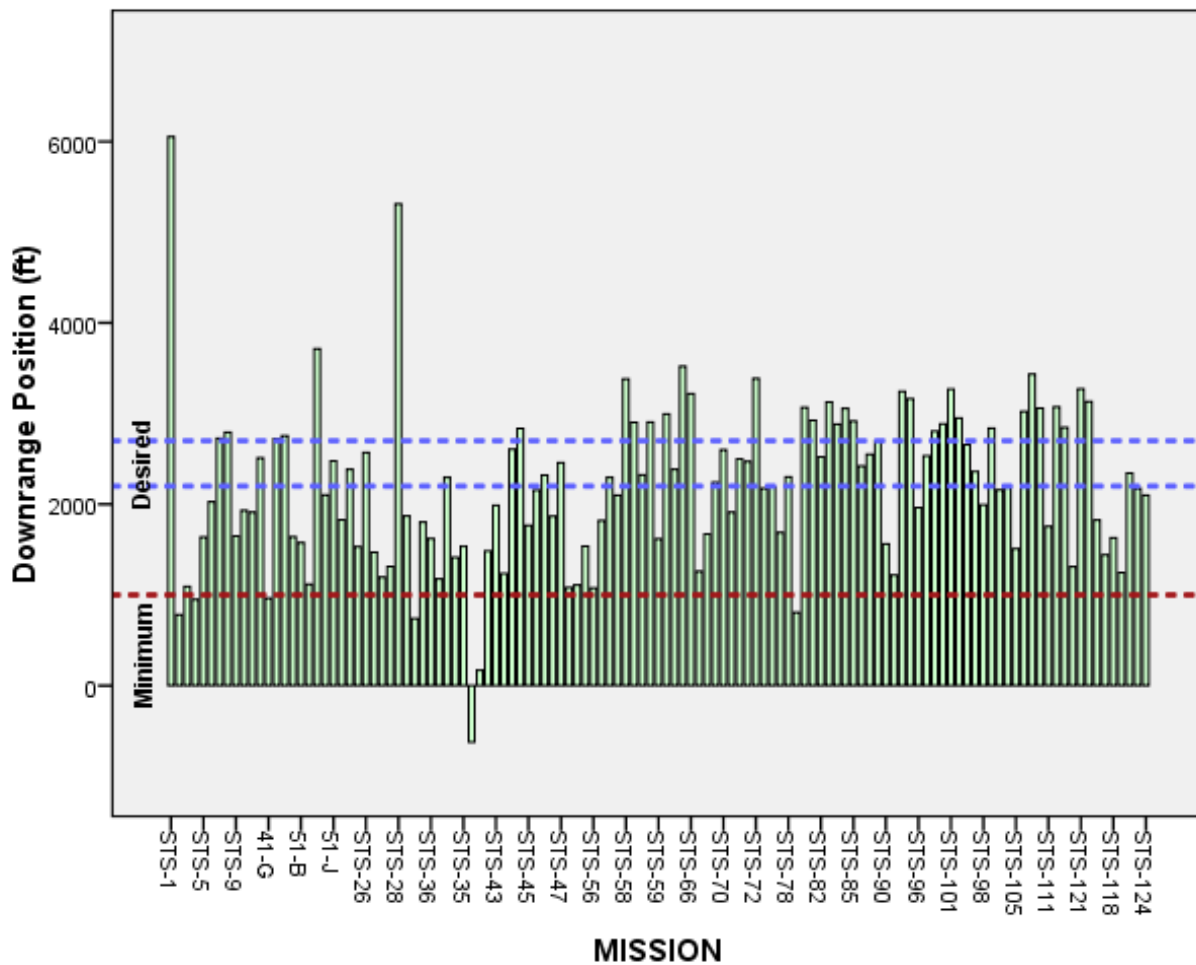
Nominal Range: 2200-2700 ft.
Pilot-Recommended Minimum: 1000 ft.
*(Landing Procedures, 4-21, p.84)*

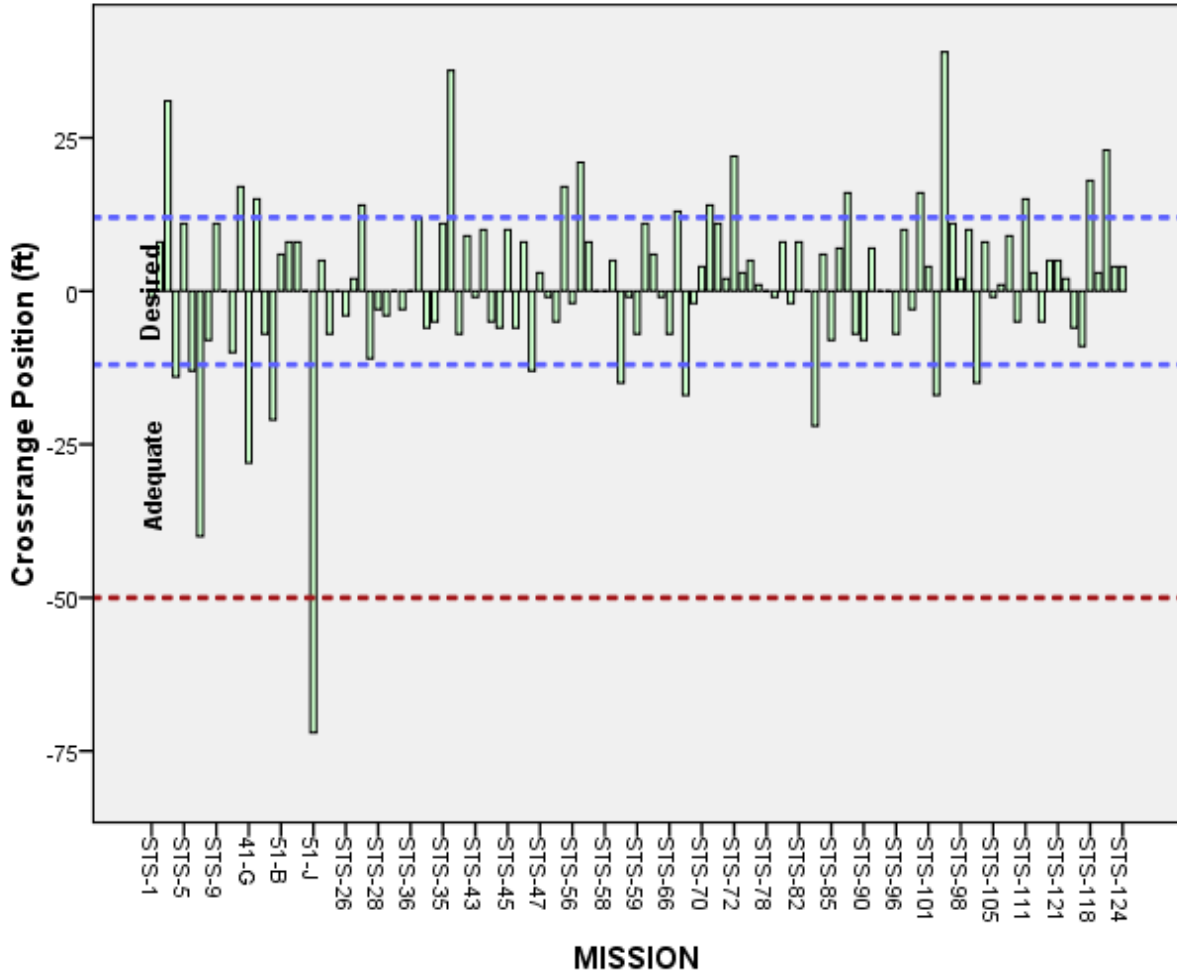62 shuttles landed short of the target minimum of 2200 feet.
7 landed less than 1000 feet from the threshold.

| MISSION | DOWNRANGE |
|---------|-----------|
| STS-37  | -623      |
| STS-39  | 169       |
| STS-33  | 740       |
| STS-2   | 780       |
| STS-79  | 807       |
| STS-4   | 948       |
| 41-G    | 962       |

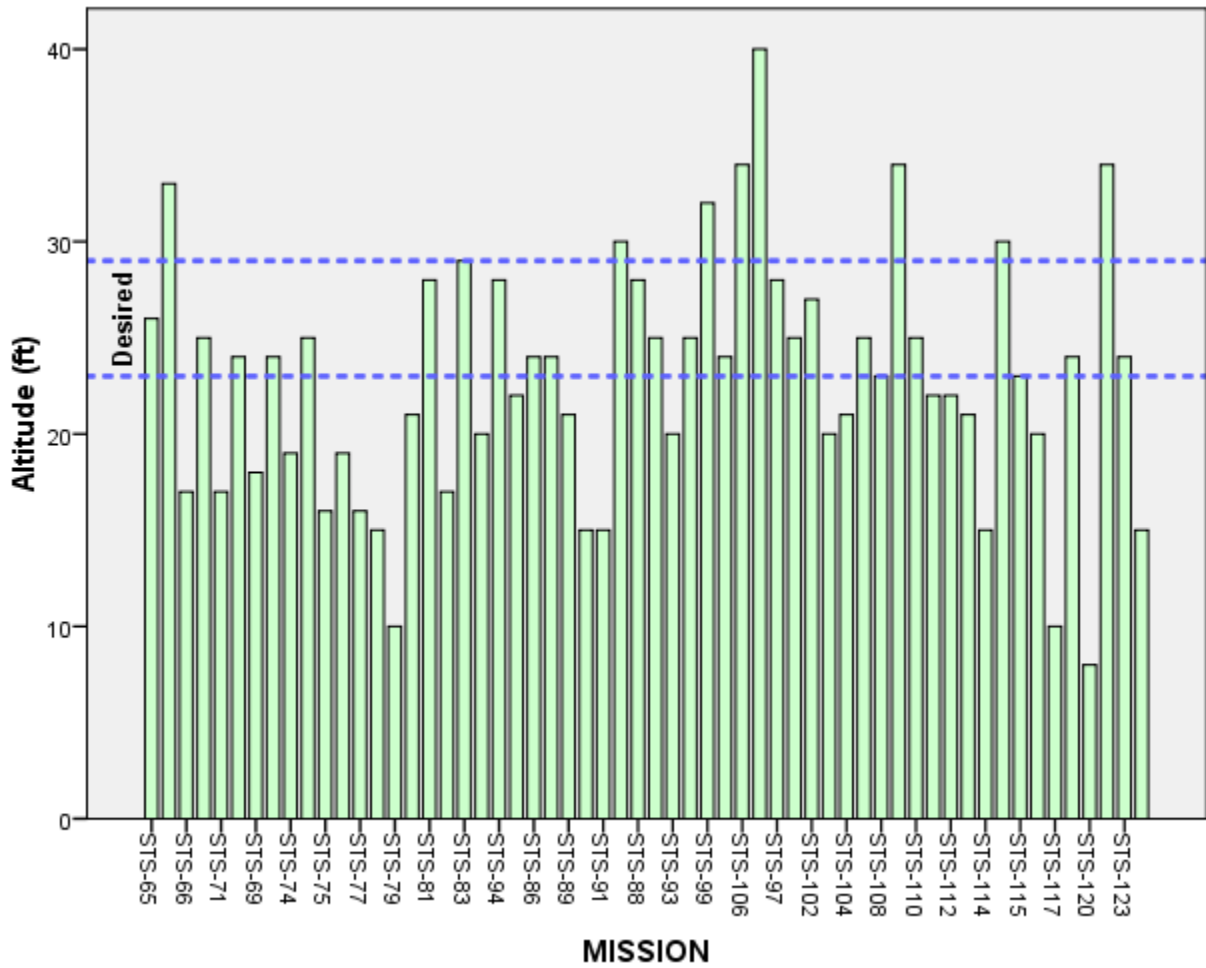**Cross range (Y-Position)**

Nominal: $0 \pm 12$.

**Altitude over Threshold**

Height over start of runway.

Nominal: 23-29 ft

NOTE: Due to the limited availability of landing this chart reflects data from 58 shuttle landings from STS-65 to STS-124.

**Sink Rate**

The sink rate, roll angle, delta heading, and y-position at touchdown are a result of atmospheric conditions and how well the commander flies the vehicle through them. The Final Flare phase is used to reduce the sink rate from about 12 fps on the IGS to less than -3 fps for touchdown. It is also used to control the time and point of touchdown so that the target touchdown airspeed is achieved.

Nominal: -2 to -3 fps, not to exceed -4 fps

13 missions had sink rates higher than -3 fps, out of which 5 missions landed with higher sink rates than the adequate -4.0 fps cutoff. STS-90 had the highest sink rate. The landing touch down appeared harder than normal. A sink rate analysis of the main landing gear was performed. The maximum allowable main gear sink rate values are 9.6 ft/sec for a 212,000 lb. vehicle and 6.0 ft/sec for a 240,000 lb. vehicle. The landing weight of the STS-90 vehicle was estimated to be 232,965 lb.

| Mission | Sink Rate |
|---------|-----------|
| 90 | -6.0 |
| 3 | -5.7 |
| 114 | -5.5 |
| 120 | -5.4 |
| 77 | -4.6 |
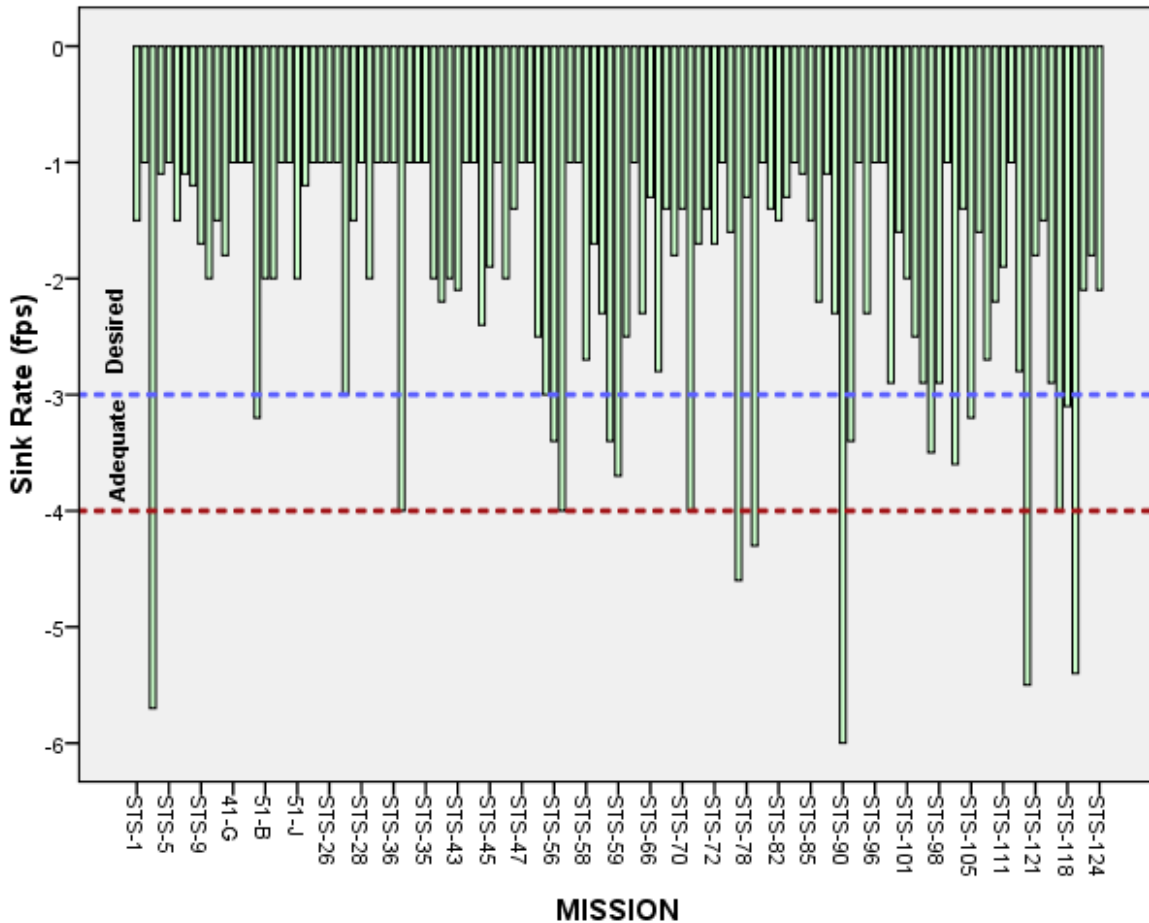
**Groundspeed**

Two potential consequences of off-nominal touchdown energies are high touchdown ground speed or excessive touchdown altitude rates. High ground speed at touchdown causes excessive tire wear during the initial spin up, which may result in a tire failure.
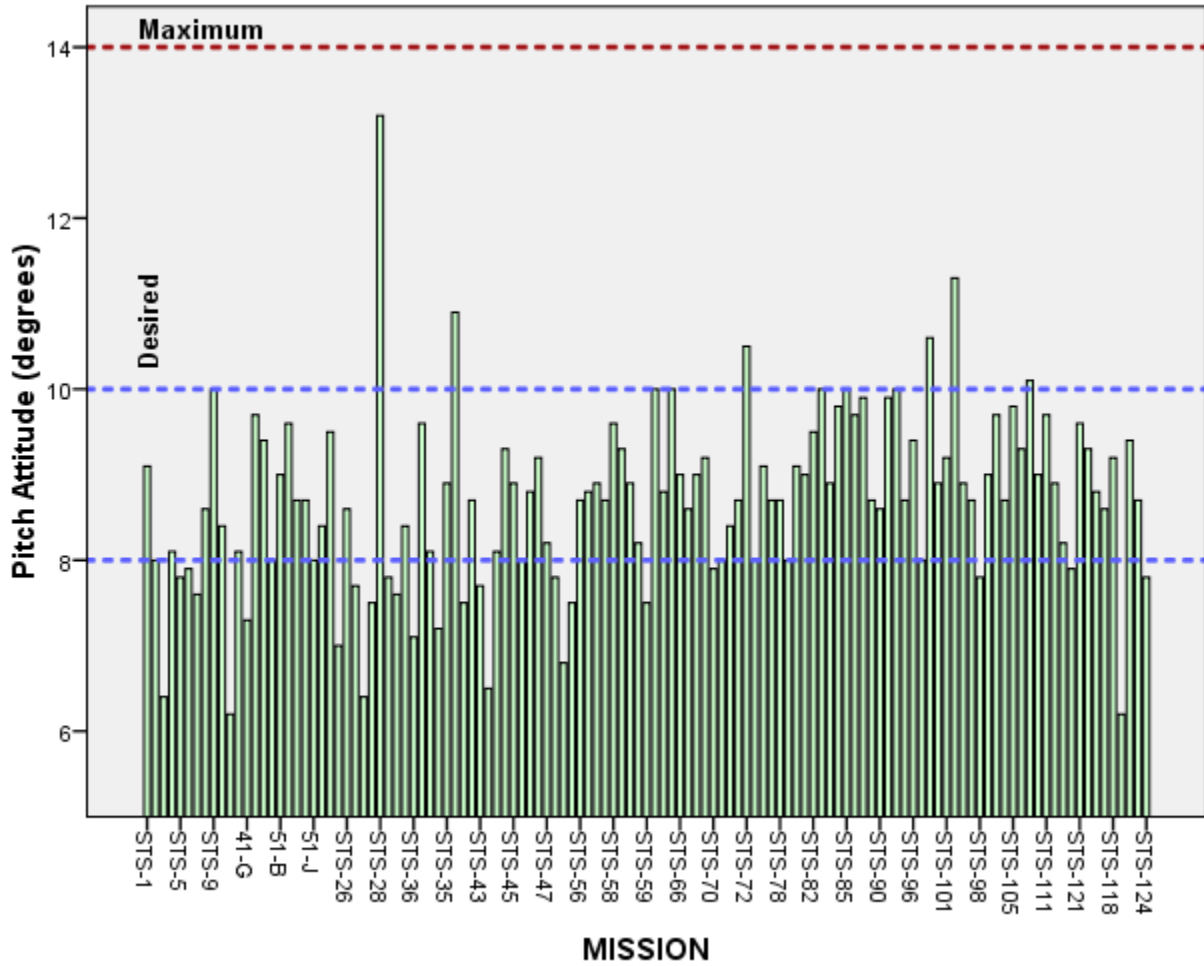
Nominal: The shuttle tires are certified to a ground speed up to 225 kts ground speed. (*Landing Procedures*, 4-25, 89)
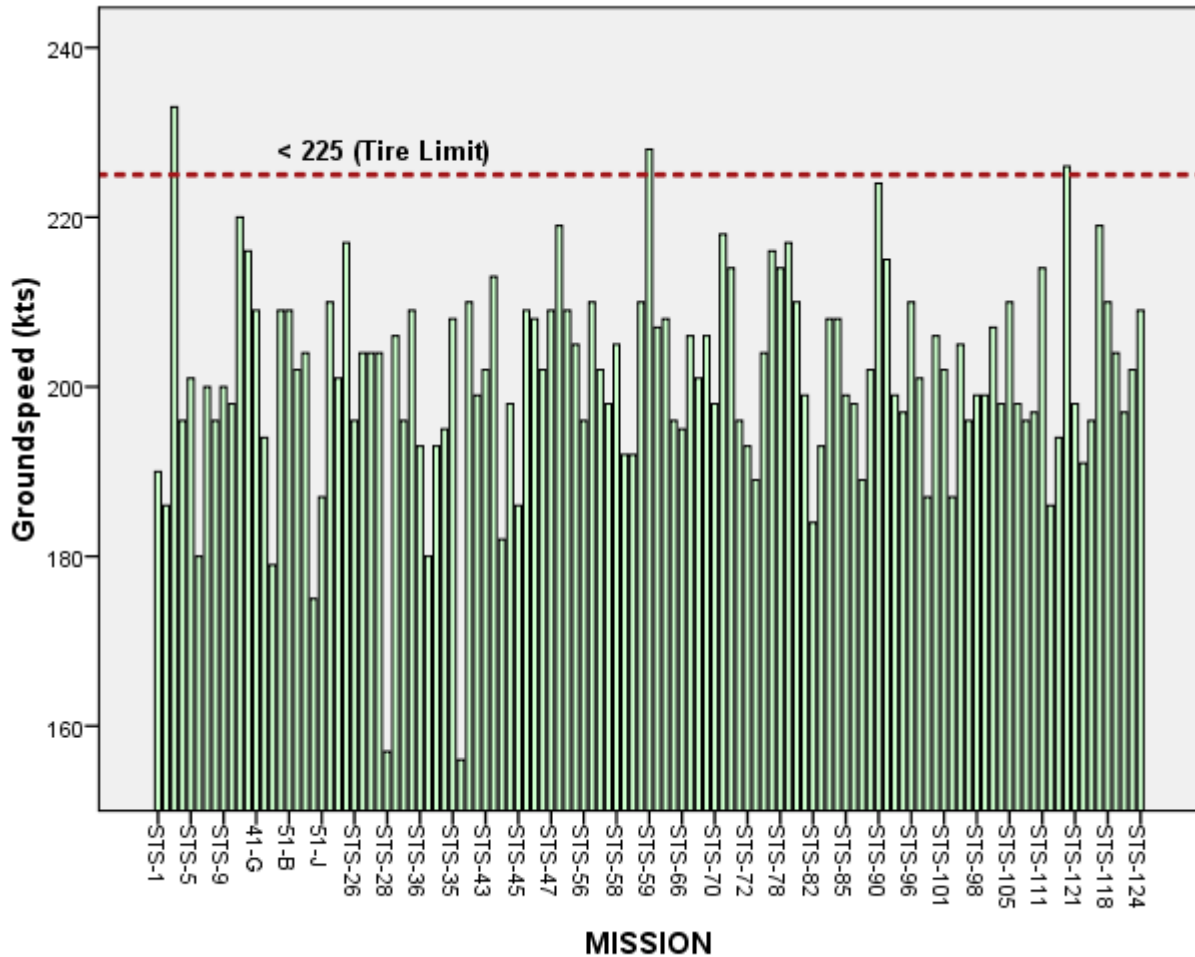
**Touchdown Pitch Attitude**

Nominal: Targeted touchdown pitch altitude is 8-10°, not to exceed 14°.
(*Landing procedures*, B-16, p.182; *USA Entry, TAEM, and Approach/Landing Guidance*, 4-13, p. 121)
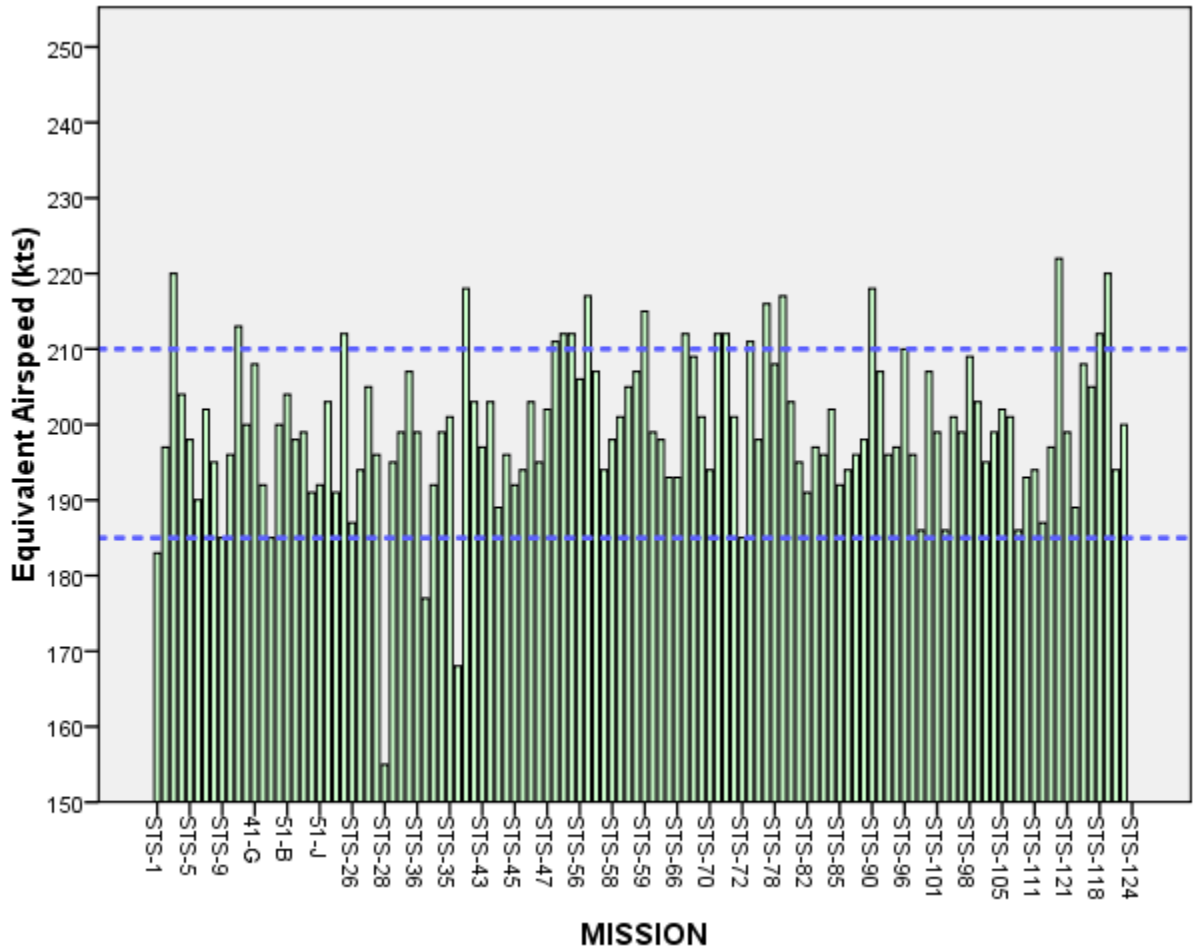
**Equivalent Airspeed**

Nominal:
    Lightweight vehicles: 195 KEAS (+5, -10)
    Heavyweight vehicles: 205 KEAS (+5, -10)

(*Landing Procedures*, 4-13, p. 77; 4-21, p.85; 4-24, p.88; *USA Entry TAEM, and Approach/Landing Guidance*, 4-13, p.122)

# XIII. APPENDIX B: APOLLO LUNAR LANDING PERFORMANCE

**Authors: Millard F. Reschke, Deborah L. Harm, William H. Paloski, Jacob J. Bloomberg, Scott J. Wood**

Surface obscuration during descent varied for each LM landing. For Apollo 11, visibility was degraded. During Apollo 12 and 15 the surface was completely obscured. For Apollo 14 and 17 LM descents, the surface was readily visible. Apollo 16 descent visibility was moderate (Wagner 2006).

Contributing factors that may be considered in mission and engineering design include:
- Landing site selection may be a factor in mission design, however, mission reports indicated that landing sites were similar, both in terms of characteristics and behavior of lunar dust.
- Improved hovering procedures may have contributed to improved visibility due to reduced blowing dust.
- Solar elevation angle may affect visibility.
- Landing radar output was affected by blowing dust and debris.

**Apollo 11 – Crew: Armstrong, Collins, Aldrin; LM: Eagle; Launch: 16-Jul-69**

First manned landing on the Moon, July 20.

Ten meters above the surface, the lander started slipping to the left and rear. Armstrong, working with the controls, had apparently tilted the lander so the engine was firing against the flight path. With the velocity as low as it was at the time, the lander began to move backward. With no rear window to help him avoid obstacles behind the lander, he could not set the vehicle down and risk landing on the rim of a crater. He was able to shift the angle of the lunar module and stop the backward movement, but he could not eliminate the drift to the left. He was reluctant to slow the descent rate any further, but the figures Aldrin kept ticking off told him they were almost out of fuel. Armstrong was concentrating so hard on flying the lunar module that he was unable to perceive the first touch on the moon nor did he hear Aldrin call out "contact light," when the probes below the footpads brushed the surface. The lander settled gently down, like a helicopter, and Armstrong cut off the engine. Armstrong was not pleased with his piloting, but landing on the moon was much trickier than on the earth. He related the maneuver to his past experience in touching down during a ground fog, except that the moon dust had movement and that had interfered with his ability to judge the direction in which his craft was moving. Aldrin thought it "a very smooth touchdown," and said so at the time. They were tilted at an angle of 4.5 degrees from the vertical and turned 13 degrees to the left of the flight path trajectory.

**Apollo 12 – Crew: Conrad, Gordon, Bean; LM: Intrepid, Launch: 14-Nov-69**

First precise manned landing on the Moon. Recovered part of Surveyor 3 probe.

As the lander passed north of Mare Nectaris, Conrad turned it on its back with the descent engine pointed along the flight path and switched the engine on to begin the final approach. Everything went exactly as expected, and after two minutes Conrad commented that it "feels good to be standing up in a g-field again." Three minutes later the module's attitude-control thrusters began firing busily - more than Conrad thought they should - but Houston assured him that all was well. After seven minutes Intrepid nosed over into a near-upright position and for the first time Conrad could see the lunar surface. The principal landmark identifying his landing point was a pattern of craters the astronauts called "Snowman"; Surveyor III lay halfway up the eastern wall of the crater that was the Snowman's torso, and Intrepid was targeted for the center of the crater. As soon as he could see out the window, Conrad cried delightedly, "Hey, there it is [Snowman]! There it is! Son of a gun! Right down the middle of the road!" Then, as Bean called out altitude, velocity, and quantity of fuel remaining; Conrad maneuvered the craft with his hand controller to pick a smooth spot to land on. The engine exhaust began kicking up dust about a hundred feet (30 meters) above the surface and by the time Intrepid reached 50 feet (15 meters) the cloud obscured the surface completely. At 1:54:36 a.m. EST on November 20, Pete Conrad made a blind landing - exactly where, he could not tell, but certainly close to the intended spot.

Conrad was naturally anxious to determine where he had set Intrepid down, and while he and Bean went through the post-landing check list they occasionally looked out the windows for landmarks that would allow Houston to pinpoint their location, but without success. After changing his mind a time or two, Conrad finally concluded, "I'm not sure that I'm not sitting right smack on the other side of the Surveyor crater, just a little bit past it." Two hours later, Dick Gordon in Yankee Clipper confirmed Conrad's guess when he sighted both Intrepid and Surveyor III through his sextant as he passed over the site. He told Houston that the lunar module was "on the left shoulder of the Snowman, about a third of the way from the Surveyor crater to the head. Post mission calculations placed Intrepid on the northwest rim of the Surveyor crater, 535 feet (163 meters) from the inert spacecraft. Had there been windows in the back of the lunar module, Conrad could have spotted the Surveyor as soon as the dust settled.

After postlanding checks of systems, Conrad and Bean described what they could see from their spacecraft. Intrepid had landed in undulating terrain pocked with craters ranging from a few feet to several hundred feet across, the larger ones rimmed by large blocks of rock. Numerous boulders, up to 20 feet (6 meters) in size, were scattered around the site, most of them angular rather than rounded, many showing fillets of dust around the base. Immediately in front of the landing craft Bean saw an area of "patterned ground" - parallel cracks in the surface soil perhaps an eighth of an inch (3 millimeters) deep. From the lunar module the crew could distinguish no color differences in the rocks or soil; everything seemed the same bright white.

**Apollo 14 – Crew: Shepard, Roosa, Mitchell; LM: Antares; Launch: 31-Jan-71**

Shepard piloted the spacecraft to a routine landing 175 feet (53 meters) from its targeted landing site.  During the final approach, they recognized Cone Crater right at pitch over and, soon thereafter, picked up the familiar pattern of smaller craters near their aim-point another mile or so to the west. There wasn't any really flat ground close at hand; there were either craters or sloping ground wherever he looked; but he had no trouble finding a crater-free, LM-sized patch that was only 30 meters from his target. The only problem with the landing spot was that it was on an eight degree slope; and, for 24 of the next 33 hours the astronauts had to contend with a tilting floor that threatened to dump Shepard over onto Mitchell's side of the spacecraft. In addition, the tilt contributed to a sleepless night between the two EVA's; but, otherwise, the LM attitude had no effect on the mission.


**Apollo 15 – Crew: Scott, Worden, Irwin; LM: Falcon; Launch: 26-Jul-71**

First mission with the Lunar Rover vehicle.

The Hadley landing area is littered with craters but, as it turned out, few are large enough or deep enough to have early morning shadows. Toward the south edge of the landing area, virtually at the foot of Hadley Delta, Scott could see a grouping called the South Cluster and, of course, the rille was out in front of him. But, out in the middle, a couple of kilometers NNW of where Scott wanted to set down, landmarks are few and far between. There are a few moderate-sized craters, which, from the pre-flight analysis, looked as though they would have shadows in them at landing time; and Scott had spent time in the simulators learning to recognize them. However, as with the Apollo 14 site, the map and model makers had missed the subtle undulations that make this a rolling countryside and make the identification of small craters difficult at best. Part of the reason was that the Apollo 15 site is well north of the Moon's equator and the photo coverage didn't have the resolution that had been available for the earlier sites; and, the net effect was at, as Scott looked out the window, he couldn't find the patterns he had hoped to see. Just before pitchover when Scott was about 6 kilometers east of the target, Houston warned him that he was probably about a kilometer south of the planned track. A quick look at his position relative to the South Cluster and to the point on the rille where it makes a sharp bend at the foot of Hadley Delta gave Scott enough information to show him that Houston's call was a good one. So, he nudged Falcon's line-of-flight toward the north. Without clear local landmarks, he couldn't be certain of setting down right on target, but he'd be close enough that the difference wouldn't matter. He was about the right distance short of the rille (now trending northwest out in front of him); he was just about due north of South Cluster; and he was well out into the middle of the desired landing area. He was certainly within a few hundred meters of the target and, with the mobility that the Rover would give them, a miss of a few hundred meters would be a matter of only a few minutes' drive. The worst that could happen would be that they would spend a few extra minutes during their initial traverse getting their bearings.

**Apollo 16 – Crew: Young, Mattingly, Duke; LM: Orion; Launch: 16-Apr-72**

First landing in the lunar highlands.

This was referred to as a 'near perfect landing.'  Young's greatest concern was the fact that there were few shadows to show him where the level spots were in this rolling terrain; and it was only in the last few moments that he got some clues from the LM shadow. It was Duke who saw the shadow first as they came down through 250 feet. Seconds later, as they were coming through 200 feet, Young rotated (yawed) the LM to the right and could see the shadow out his own window and use it to estimate his altitude and the sizes of the craters ahead. Through a combination of skill and luck, he set down on a remarkably level spot. As he and Duke discovered once they got outside, had they landed 25 meters in any direction from the actual landing site, [the LM] would have been on a local slope of six to ten degrees. In particular, in the final seconds, Young had to hover so that he could fly forward and to the right, just beyond a small crater fifteen meters in diameter. Only Armstrong and Conrad landed more upright, and both had the advantage of young, lightly-cratered, mare sites.

**Apollo 17 – Crew: Cernan, Evans, Schmitt; LM: Challenger; Launch: 7-Dec-72**

Final Apollo lunar mission.

Both crewmembers saw dust by 60-70 feet, although visibility through the final phase was excellent.  "The tendency, once you redefine your landing area, is to become less concerned with your peripheral landmarks… you get more tunnel vision, and you are concerned with finding these specific touchdown points within that landing area. … I can't say enough for what I consider the accuracy of the guidance.  Manual control of the spacecraft was hard and firm … exactly what I expected it to be."

**Sources for Apollo Guidance/Navigation Information:**

Apollo Lunar Surface Journal (mission reports, transcripts, etc.):
http://www.hq.nasa.gov/alsj/frame.html

NASA Document Index System (DIS)
http://www6.jsc.nasa.gov/dis/

Manned Spaceflight PDF Documents
http://www.geocities.com/bobandrepont/spacepdf.htm

JSC Engineering Directorate
http://ea.jsc.nasa.gov/Ea_web/HTML/index.asp

Working on the Moon (Lessons from Apollo)
http://www.workingonthemoon.com/index.html

NASA Human Space Flight
http://spaceflight.nasa.gov/history/shuttle-mir/people/oral-histories.htm

**People contacted:**
Eric Jones (editor, Apollo Lunar Surface Journal)
David Woods (Author: "How Apollo Flew to the Moon")
Floyd Bennett (designed the approach trajectories)
Ken Young (Apollo flight veteran)
Kim So (Library Technician)
Michele Hendershot (MOD Chief Curator)
Thomas Jones (astronaut)

**Documents:**
Lunar Module Timelines (Apollo 12, 14, 16)
Aerodynamic Stability Characteristics of the Apollo Command Module
Postflight Entry Analysis
Mission Reports
Technical Reports
GNC Performance Analysis (Apollo 8, 9, 14, 15, 16)
Apollo Experience Report: Mission Planning for Lunar Module Descent and Ascent
Lunar Descent and Ascent Trajectories
A Study of Lunar module Navigation Systems Accuracies for Powered Descent, Ascents and
   Aborts
Study of Powered Descent Trajectories for Manned Lunar Landings
Downloaded several videos on Apollo Falls from various missions
Analysis of Apollo Navigation Accuracy

# XIV. APPENDIX C: INCIDENTS DUE TO SITUATIONAL AWARENESS DURING EVA

**Authors: Millard F. Reschke, Deborah L. Harm, William H. Paloski, Jacob J. Bloomberg, Scott J. Wood**

**MSS Lessons Learned**
**DX23 / ISS Mechanical & Robotics Systems Training**

April 18, 2007

**Scope of Lesson:**
This lesson is intended to inform crewmembers assigned to Station Robotics about the historical issues that have been overcome and why the system is operated the way it is today. The Robotics training flow is designed to gain generic understanding for operating the system as well as flight specific task familiarization. The operational habits discussed in this lesson apply to operating in both familiar and unfamiliar circumstances. These habits reinforce Space Flight Resource Management (SFRM) habits of Leadership, Communication and Situational Awareness. Many of the issues stem from failures in one or more of these areas.

**MSS Close Call Flight Incidents:**

**1. PDGF "Stiction" Problem**

*Situation:*
Crew was releasing and backing off a grapple fixture. The normal method for this is to send an auto release command and the system relieves tension, opens the snares and extends the carriage forward. After the snares are opened, the operator starts backing off the grapple fixture so the carriage does not bump the fixture and pin. During this release the Latching End Effector (LEE) became stuck in the grapple fixture. Operator observed no motion so input higher hand controller command (building up forces in the arm). As the carriage moved forward it pushed the LEE off of the grapple fixture. The arm sprang off the fixture due to the force buildup and recoiled back striking the grapple fixture and lab (actual contact made and heard by crew inside).

*Contributing factors:*
Situational Awareness - Loss of Situational Awareness of overlays and video. Not sure if crew noticed the overlay data indicating high command inputs but no actual motion. Video also showed no motion. If the crew noticed they did not react in time to prevent hitting.

*Operational Changes:*
Situational Awareness - Education of crew on stiction problem - Train the crew on the signatures of a sticky grapple fixture. Overlay will indicate high level of commanded input but little to no actual FOR motion. Video will not show motion. Input should be removed immediately to limit arm force build up.

Changes to release technique - After this incident the ground team investigated causes of the stiction.  No root cause has been determined but for expected grapple fixtures and scenarios a "push-off" technique is used to release.  This technique allows the carriage to extend and "push" the LEE off the grapple fixture.


2. **ISS-7A / STS-104 Close Call**
   **Space Station Remote Manipulator System (SSRMS) to Ultra High Frequency (UHF) Antenna Close Call**

**Situation:**
- The crew got ahead in the timeline and decision was made to install a third oxygen/nitrogen tank (ONTO).  Tank was grappled by the SSRMS and handed off to EV crew at the airlock.  At the end of the handoff the crew was asked to park the arm at a known location but the trajectory to get there was unfamiliar since the crew had not trained flying to a park position from the third tank install location.
- The big picture camera (Camera C on the Orbiter) was zoomed in on EV crew installing the ONTO tank while the arm was being maneuvered to park.  This stage of assembly utilized station crewmembers for robotics operations and all three crewmembers were trained on the tasks.  This maneuver was very late in the crew day and the "least" trained operator was performing this "simple" maneuver.  The arm was maneuvered well away from structure and hit a six-degree of freedom (6 DOF) singularity causing the elbow to swing toward the UHF antenna.  Eventually the camera C view was zoomed out to see whole arm, but elbow to UHF clearance not discernable.  Good orthogonal camera views did not exist due to station configuration (no outboard structure yet to house a camera).  Ground made a call to stop the arm and the Lab window was utilized to view actual clearance between arm and antenna.  The ground tools showed 2 inches of clearance between arm and antenna when the arm stopped.
- The arm was maneuvered using a joint held algorithm.  If a singularity was encountered, the arm would release the held joint and manage the singularity.  This was identified by sluggish FOR motion, moving joint indication and pitch plane change (elbow joint swing) of the arm.

**Contributing Factors**
- Situational Awareness - Poor camera views - Crew had no big picture view.  What had been a big picture view earlier, Cam C was left zoomed in on the ONTO.  Crew was reluctant to ask shuttle crew to adjust cam C.  Also the lack of cameras at this stage of assembly limited visibility into some clearances.
- Long Day, Tired Crew - The nominal plan for the day was to do two tanks, but they were ahead in the timeline and crew agreed to press with the third tank.  After the mission, the crew reported that the arm ops were both physically and mentally draining.

- Unscripted Task/Unscripted Operator - There was never a plan or procedure to go from the 3rd ONTO to Lab FRGF.  Therefore, this trajectory was never evaluated on the ground for clearance or singularities.  This took them into the SY or WY singularity.  Although the SSMRS Operator was fully certified on SSRMS, they had no experience operating in this area of the ISS.  The operator that flew this last maneuver of the day was not the same operator that flew the EVA task just prior (the crew switched off operators).
- No Full-Time M2 - Because the day was longer than expected, the M2 was trying to do two jobs: M2 role and helping with IV Ops as EVA crew were ingressing the Airlock.  M2 was not fully engaged in the final task.
- Crew was unaware of singularity indications - Crew was never trained to identify a singularity condition based on "sluggish" FOR motion, joint release and elbow swing.  Generic Robotics Training and Spec Skills flow did not exist in this timeframe.

**Operational Changes:**
- Improvements in Communication - "All stop on the arm" voice protocol implemented - The call to crew was not very clean nor quick.  A formalized method for declaring and implementing an All Stop was developed for both the Station and Shuttle Arm.  Caution was taken to make the call and response similar for each system so cross trained crews would not be confused.  New method has the person identifying the emergency issue declare all stop three times (All Stop, All Stop, All Stop).  If heard the operator releases the hand controllers and safes the system.  If called during a docked mission both the Shuttle and Station arms react to the same call so there is no reason to discern between the systems in trouble.
- Tight clearance scenarios implemented in Generic simulations & MSS lessons - The training team developed a series of scenarios and lessons to exercise tight clearance situations and unscheduled trajectory flying.
- Improvements in Situational Awareness - "Joint release" computation developed for the Mission Control Center (MCC) - The ground created an indication that the held joint had released.  This would alert the ground team to possible elbow swing and they could make the call to crew.


3.  **ISS-8A / STS-110**

   **Operational Changes:**
   No issues occurred during this mission that were SFRM errors.  The arm did have a joint failure prior to flight, which was worked around using procedures and software changes.  Operational changes came during training.  The areas the arm was operating for the flight had numerous 6 DOF singularity zones. To avoid the earlier issues the community decided to start locking joints, which disabled the singularity management.  If a singularity was encountered, the arm would simply stop and the team could decide how to continue with the task.  Also in this timeframe the software was updated to include crew annunciations of

6 DOF singularities and enhancements to the Dynamic Onboard Ubiquitous Graphics (DOUG) tool provided better Situational awareness to the crews.


4. **ISS-UF2 / STS-111 Close Call**
   **SRMS to SSRMS Close Call**

**Situation:**
During a scheduled EVA activity, both the Shuttle and Station robotic arms were being used in close proximity to each other. The EV crews were directing the motion of both arms (called Ground Control Assist or GCA). At one point the two arms were moving at the same time toward each other. The ground called to have motion stopped (new All stop protocol was still being worked out so not utilized). Actual arm-to-arm distance is unknown but inside of desirable 5 feet.

**Contributing Factors:**
- Communication - Shuttle and Station arm operators were not coordinating motion. Communication between Shuttle and Station operators and ground teams not ideal in this scenario. There was no documented rules stating how to handle this situation.
- Situational Awareness - M1 not familiar with procedure. At this stage in assembly the Station crew was still utilized for arm operations and often times paired with a shuttle crewmember. Since Station crews could launch months ahead of the Shuttle mission, training the M1 and M2 together for tasks was very difficult to schedule. Many times the procedure would change after the Station crew had launched and they would have to adapt to those changes in real time.
- Communication and Situational Awareness - EV providing GCA to both arms. EVA tasks were happening in parallel and neither EV crew was very aware of the arm locations.

**Operational Changes:**
- Improvements in Situational Awareness - Ground developed a flight rule to minimize dual arm motion when in close proximity to each other. The flight rule (FR C12-7) states that simultaneous motion is allowed if 5 feet between the arms is maintained.
- Camera conflicts are minimized pre-flight since the Station and Shuttle arm operators can and do share cameras.
- Improvements in Communication - Shuttle and Station ground teams work together to develop a choreographed plan for arm motion. Procedures now contain callouts and sync points between the arms to minimized unnecessary dual motion. An example would be a callout in the Station procedure that says "give a go to the SRMS to maneuver to Install viewing position". The Shuttle procedure would then say "Notify Station when at Install viewing position".

5.  **ISS-9A / STS-112 Close Call**
    **SSRMS Elbow to PLB Door Close Call**

**Situation:**
During an EVA task the arm was in a closed configuration (not ideal).  The EV crew was giving GCA calls to maneuver the arm and was helping some with helmet video views of clearances.  This particular maneuver required rotation and translation commands in a particular sequence to limit the elbow swing of the arm.  This swing was due to arm configuration (closed up so a very small angle between the tip and base booms) and not singularities.  The crew was aware of the elbow swing from training.  They had notes indicating how to avoid this effect.  During the maneuver the prime camera for the elbow (Camera C from the Orbiter) got washed out with sunlight.  Crew switched to a backup camera but mistook a box on the arm for the elbow so lost sight of closest object.  The maneuver was flown as trained but response was not as expected and the elbow started to swing toward the Orbiter payload bay door.  The All Stop was called by the ground and the proper response was issued.  When the arm came to stop the ground tools indicated contact but no evidence of this was seen onboard (i.e. no damage to arm or door).  Actual distance is unknown.

**Contributing Factors:**
- Situational Awareness - Poor camera views.  Crew lost the big picture view when Camera C was washed out.  The backup view was misused when they thought they had the elbow in one of their scenes but the object turned out to be a box on the arm.
- Maneuver known to potentially cause large Elbow Pitch joint motion due to proximity of the tip of the SSRMS to its base.  Crew was aware of the issue through training and had details in their crew notes concerning this maneuver.
- The technique used for the maneuver was not performing as expected.  Crew made simultaneous translation and rotation inputs.  Performing the rotation corrections first, minimizes the unwanted elbow joint motion.  Crew commented that the on-orbit rotation response seemed less than what they had experienced during training.

**Operational Changes:**
- Improvements to Situational Awareness - Ground now has camera pan/tilt data which can be sent to their clearance monitoring tool.  This will help identify what the crew is watching and the ground team can direct them if they are watching something incorrectly.  Crew is now provided with pan and tilt data in procedures so they can know they are looking at the proper things.
- Limit unscripted manual mode use.  The arm is now maneuvered primarily by auto sequences or single joint mode.  The manual operations are reserved for small EVA

maneuvers to final worksite and grapples. This allows the ground to evaluate issues and contingencies from known positions. The ground also designs better arm configurations for tasks to avoid having the arm closed up on itself.

- Improvements to Communication - Established sync points for communicating with EV crew and ground.

**6. ISS-11A / STS-113 Incident**
   **Mobile Transporter hit the stowed P1 UHF Antenna**

**Situation:**
During this mission the Mobile Transporter (MT) was timelined to translate after the deployment of the antenna. The EVA to deploy the antenna got behind and the deploy was delayed. The decision to translate was not altered and during the maneuver the MT ran over the antenna. When it hit, the ground didn't know what was going wrong. An EVA Crew inspection determined a box on the MT was hitting the UHF antenna on P1. The EV crew deployed the UHF antenna so the MT translation path was clear. Analysis failed to realize the antenna in its stowed state was in the translation corridor for the MT. There was some damage to the MT box but the antenna was fine.

**Contributing Factors:**
- Situational Awareness - Camera views were not required for the maneuver. Translation analysis had been done with P1 UHF antenna deployed since this was the expected configuration. During the fit test at Cape Canaveral, the UHF antenna was deployed, and they didn't check to see if the MT would fit past the antenna if it was stowed.
- P1 UHF antenna deployment was delayed because the EVA activity ran long. Failure of the ground team to determine the impact this might have on the translation.

**Operational Changes:**
Improvements to Situational Awareness - A flight rule now exists (FR B12-5) that states a CCTV survey of MT translation path is required before motion.

**7. Other Onboard Events**

**Situation:**
There have been several events where operators have made input errors in typing auto sequence numbers. All but one was caught prior to motion. The event where motion occurred was minor since only the wrist roll joint moved. Typically there are several checks in place to assure proper entry of numbers. Breakdown in these checks have led to the mistakes. Breakdowns include having solo operators (no second set of eyes to verify what was entered or what should be entered), Crew fatigue (performing operations late in a crew's day) and improper mismatch or use of the M1 and M2.

**Contributing Factors:**
- Situational Awareness - Crew fatigue can lead to omitting or adding a sign change in the typed number. Can also lead to moving a decimal place or transposing numbers.
- Communication - Solo operations (without an M2) has led to issues.
- Leadership - Improper use of an M2 can lead to problems.

**Operational Changes:**
- Improvements in Situational Awareness - Educating the crew on when they are fatigued and steps they should take when they are in this state. Training touches on this by putting crews in timed situations adding pressure and trying to overload the operator. Educating the ground to be aware of what they are asking the crew to perform and the timing of the request (i.e. don't schedule tasks very late in the day without taking extra precautions).
- Improvements in Communication - New Ground rules and constraints are being generated to indicate the types of operations that can be done solo and which ones require an M2. There are also rules being generated to detail what steps should be taken if an M2 is not available. This includes more sync points with the ground and possible communication with station requirements for the operation to proceed.
- Improvements in Leadership - Steps are being taken to properly match skill levels of M1 and M2 operators. Keeping skill levels the same minimizes the chances that one operator will get ahead or behind the other. Training has developed a lesson to educate operators on proper M1 and M2 habits and roles. All arm operators take this class.

**Summary**

Robotics community has gained knowledge & experience. Operators' prevention goes back to SFRM basics of Command/Leadership, Communication/Workload Management, Situational Awareness and Decision Making. Ground has better mission design tools and real-time data. Today the arm is flown with limited Manual mode use, locking joints to limit singularity management, and rules are in place for coordinating and carrying out tasks. Procedures now contain Clearances, task unique item notes, coordination calls, sync points. Training has been updated to include the lessons learned in this class and throughout the training flow. There is no guarantee there will not be other incidents but the hope is the measures implemented will greatly reduce or eliminate the occurrences in the future.