Chapter 3

The Neuro-Sensory System in Space

To be aware of the environment, one must sense or perceive that environment.[1] The body senses the environment by the interaction of specialized sensory organs with one aspect or another of the environment. The central nervous system utilizes these sensations to coordinate and organize muscular movements, shift from uncomfortable positions, and adjust properly. One relevant question is "what is the relative contribution of gravity to these sensory and motor functions?" This chapter reviews the effects of microgravity on the functioning of the sensory organs primarily used for balance and spatial orientation. Disorientation and malaise so frequently encountered during early exposure to microgravity and upon return to Earth are described. Theories and actual data regarding the role of the central nervous system in the adaptation of sensory-motor functions, including the control of posture, eye movements, and self-orientation, to changing environmental gravity levels are explored. For a comprehensive review of space research conducted in this area since the beginning of spaceflight, the reader is referred to the book *Neuroscience in Space* [Clément and Reschke, 2008] (Figure 3.1).

3.1. The problem: space motion sickness

The neuro-vestibular system consists of organs sensing the acceleration environment, nerves transmitting this information to the spinal cord and brain, and the central nervous system (CNS) that integrates this information so that we can determine our position and orientation relative to the environment. The vestibular organs in the inner ear detect and measure linear and angular accelerations. These responses, already complex, are further integrated with visual and proprioceptive inputs (Figure 3.2). In microgravity, some of these signals are modified, leading to misinterpretation and inadequate responses by the brain. One of these responses is space motion sickness (SMS) (Figure 3.3).

SMS is a special form of motion sickness that is experienced by some individuals during the first several days of exposure to microgravity. The syndrome may include such symptoms as depressed appetite, a nonspecific malaise, lethargy, gastrointestinal discomfort, nausea, and vomiting. As in other forms of motion sickness, the syndrome

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[1] The words "sense" and "perceive" are from Latin words: "sense" means "to feel", whereas "perceive" means "to take in through", i.e., to receive an impression of the outside world through some portion of the body.

G. Clément, *Fundamentals of Space Medicine*, Space Technology Library 23,
DOI 10.1007/978-1-4419-9905-4_3,

Figure 3.1. Astronauts on Board the ISS Wear Different Colors and Patterns of Polo Shirts for Ease of Identification of Crewmates When They Are Not Right Side Up. (Credit NASA).

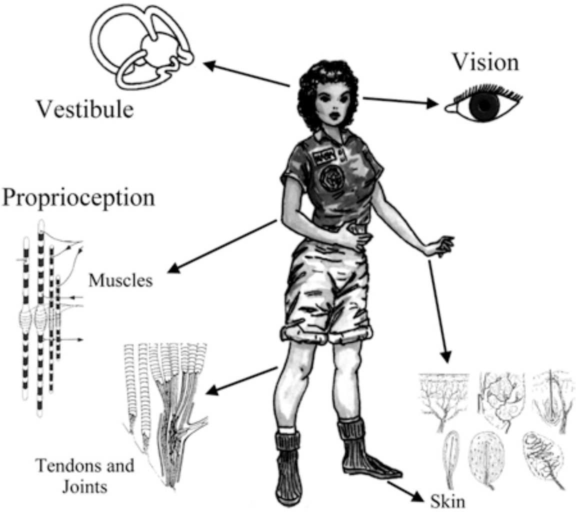

Figure 3.2. The Eyes, the Inner Ear and the Special Receptors in the Skin, Muscles and Joints All Participate in Maintaining Posture and Balance, and Assist in Our Movements.

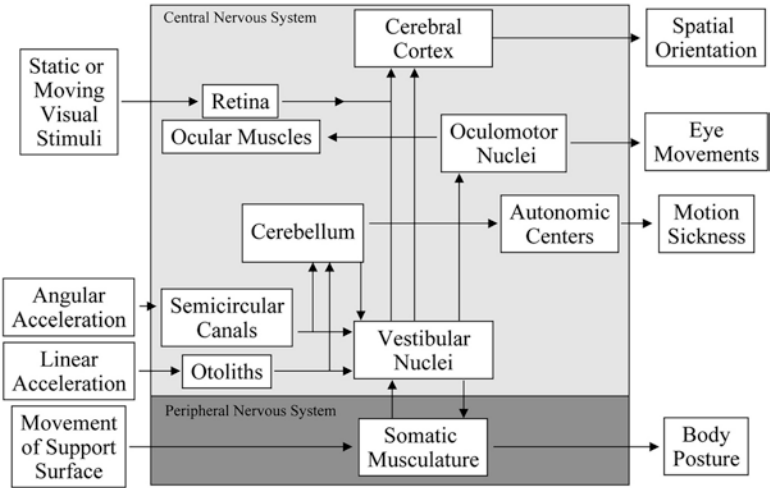

Figure 3.3. Inputs and Outputs of the Neuro-Vestibular System. The Information from the Various Sensory Organs First Reaches the Brainstem and Cerebellum. We Are Not Consciously Aware of What Is Going on in Our Busy Body When We Sit, Stand, Walk, or Run. However, Certain Sensations Do Eventually Reach the Cerebral Cortex, and Through Them We Remain Consciously Aware of the Relative Positions of Our Body Parts. Motion Sickness Might Be Caused by a Conflict Among Sensory Inputs Through Connections with the Autonomic Nervous System.

may induce an inhibition of self-motivation, which can result in decreased ability to perform demanding tasks in those persons who are most severely affected. Gastrointestinal symptoms have their onset from minutes to hours after orbital insertion. Excessive head movement early on-orbit generally increases these symptoms. Symptom resolution usually occurs between 30 and 48 h, with a reported range of 12–72 h, and recovery is rapid.

Even if someone doesn't literally get sick to their stomach, they may feel a less dramatic motion sickness effect known as "sopite syndrome", characterized by lethargy, mental dullness, and disorientation. Many astronauts have noticed this effect, which they call "mental viscosity," "space fog," or "the space stupids."

There were no reports of SMS in the Mercury and Gemini programs, while 35% of the Apollo astronauts exhibited symptoms. The incidence during the *Skylab* missions increased to 60%. About two-thirds of the space shuttle astronauts and *Soyuz* cosmonauts experienced some symptoms of SMS. There are no statistically significant differences in symptom occurrence between pilots versus non-pilots, males versus females, different age groups, or novices (first time flyers) versus veterans (repeat flyers.) An astronaut's susceptibility to SMS on his/her first flight correctly predicted susceptibility on the second flight in 77% of the cases [Davis et al., 1988]. In other words, one astronaut who has been sick during his or her first flight is likely to be sick again during subsequent flights.

SMS affects a similar percentage of both U.S. and Russian crews. Symptom recurrence at landing, also called "Mal de Débarquement," reportedly afflicts 92% of Russian cosmonauts returning from longer missions [Gorgiladze and Bryanov, 1989]. No reports of *mal de débarquement* were noted in the space shuttle program. However, many astronauts returning to Earth after long-duration stay on board the ISS now experience this syndrome. The severity of the symptoms and the functional recovery after the flight seem to be directly proportional to the time on orbit.

Microgravity by itself does not induce space sickness. There were no reports of motion sickness during the Mercury and Gemini spaceflights. As the volume of spacecraft has increased, allowing for more mobility, the incidence of SMS has increased as well. Movements that produce changes in head orientation seem necessary to induce SMS symptoms. In particular, many crewmembers report that vertical head movements (rotation in the pitch or roll planes) are more provocative than horizontal (yaw) head movements [Oman et al., 1990]. However, once sickness has been well established, head movements in any plane are generally minimized by the affected crewmember. Indeed, movement of any kind is frequently restricted until the astronaut is on the road to recovery.

Head or full body movements made upon transitioning from microgravity to a gravitational field less than that on Earth, and vice versa, may not be as provocative. It is interesting to note that of the 12 Apollo astronauts who walked on the Moon, only 3 reported mild symptoms, such as stomach awareness or loss of appetite, prior to their EVA. None reported symptoms while in the one-sixth gravity of the lunar surface, and no symptoms were noted upon return to weightlessness after leaving the Moon surface [Homick and Miller, 1975].

There are considerable individual differences in susceptibility to SMS, and currently it is not possible to predict with any accuracy those who will have some difficulty with sickness while in space. Although anti-motion sickness drugs offer some protection against SMS, some drugs (i.e., scopolamine) may interfere with the adaptation process, and symptoms controlled by these drugs are experienced again once treatment ceases.

Symptoms have rarely occurred during extravehicular activity (EVA). Because most space sickness has abated by the third day of flight, mission rules restrict EVAs until the third mission day. Nevertheless, some astronauts medicate prior to space walking. The minimum flight duration for the space shuttle was also 3 days, to reduce the probability for astronauts, in particular the pilots, to be incapacitated by SMS symptoms prior to re-entry and landing [Davis et al., 1988]. The fact that the shuttle and *Soyuz* dock to the ISS only after having spent 2 days in orbit reduces the occurrence of SMS in the crew when arriving in a large open space such as the ISS.

Other issues related to the adaptation of the central nervous system through the vestibular pathways include: (a) the perceptual effects and illusions of free-falling, visual reorientation illusions, and acrophobia episodes (fear of height) during EVA; (b) decreased sensorimotor performance and visual scene oscillation (oscillopsia) during re-entry; (c) disequilibrium and ataxia when standing and walking after landing; and (d) g-state flashbacks during unusual stimulation of the vestibular system during the re-adaptation period following landing.

3.2. Vestibular function

The gravity vector is a fundamental factor in human spatial orientation, which results from the integration of a complex of sensory inputs coming from the vestibular organs in the inner ear, the eyes, mostly from peripheral retina, and tactile and proprioceptive receptors located in the skin, joints, muscles, and viscera.

3.2.1. The vestibular system

3.2.1.1. The vestibular end organs

The vestibular system's main purpose is to create a stable platform for the eyes so that we can orient to the vertical – up is up and down is down – and move smoothly. The inner ear contains two balance-sensing systems: one is sensitive to linear acceleration, the other to angular acceleration (Figure 3.4).

The linear acceleration sensing system sends messages to the brain as to how the head is translated or positioned relative to the force of gravity. It contains two tiny sacs filled with fluid, the saccule and the utricle, lined along their inner surface with hair cells of various lengths. Overlying the hair cells is a gelatinous matrix (the otoconia) containing solid calcium carbonates crystals (the otoliths, meaning "ear stone" in Greek). During linear acceleration, the crystals, being denser than the surrounding fluid, will tend to be left behind due to their inertia. It has been demonstrated that the resultant bending of the cilia causes cell excitation when the bending is toward the kinocilium (the longest hair cell), and inhibition when away from the kino-cilium. During head motion, the weight and movement of the otoliths stimulate the nerve endings surrounding the hair cells and give the brain information on motion in a particular direction (up, down, forward, backward, right, left) or tilt in the sagittal (pitch) or the frontal (roll) plane.

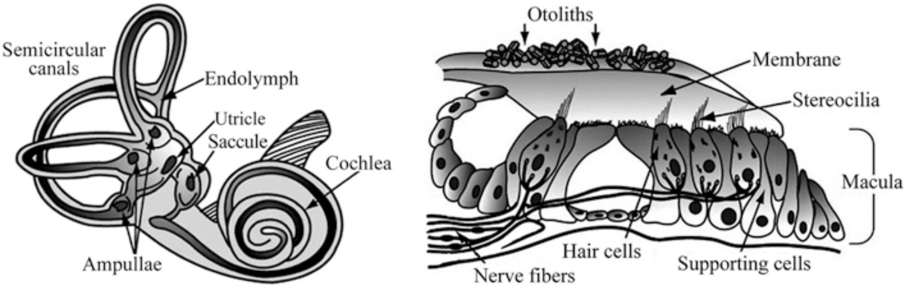

Figure 3.4. ***Left*: Schematic of the Vestibular System in the Inner Ear Showing the Three Semicircular Canals (Anterior, Posterior, Horizontal) and the Two Otolith Organs (Utricle and Saccule). *Right*: Otoliths Are Small Particles of Calcium Carbonate in the Gel-Like Membrane Layer Situated Over the Sensory Hairs (Stereocilia) of the Utricles and Saccules.** When the Head Moves or Is Tilted Relative to Gravity, the Membrane Exerts a Shear Force on the Cilia, Which in Turn Stimulates the Hair Cells. The Hair Cells Signal the Corresponding Information Via the Nerve Fibers to the Central Nervous System, Where the Sensation of Motion or Tilt Results.

The angular acceleration sensing system comprises three semicircular canals. The system detects angular acceleration through the inertial movement of the liquid (the endolymph) within each canal and provides the brain with information about rotation about the three axes: yaw, pitch, and roll. The semicircular canals do not react to the body's position with respect to gravity. They react to a change in the body's position. In other words, the semicircular canals do not measure motion itself, but change in motion. Not surprisingly, the semicircular canals are not affected by spaceflight, as shown by the absence of changes in the perception of rotation or in the compensatory eye movements in response to rotation both in-flight and after flight (see Section 3.3.5 below).

3.2.1.2. Linear acceleration and gravity

When our head is horizontal the hair cells in the utricles are not bent and this stimulation is interpreted as signifying "normal posture". If our head is tilted forward, the otoliths shift downward under the action of gravity, bending the hair cells. If we translate backward, again there is a shift of the otoliths forward due to the inertial forces. Thus, an equivalent displacement of the otoliths (and consequently the same information is conveyed to the central nervous system) can be generated when the head is tilted 30° forward, or when the body is translating at 0.5 g backward (Figure 3.5). This example simply illustrates Einstein's principle stating that, on Earth, all linear accelerometers cannot distinguish between an actual linear acceleration and a head tilt relative to gravity.[2]

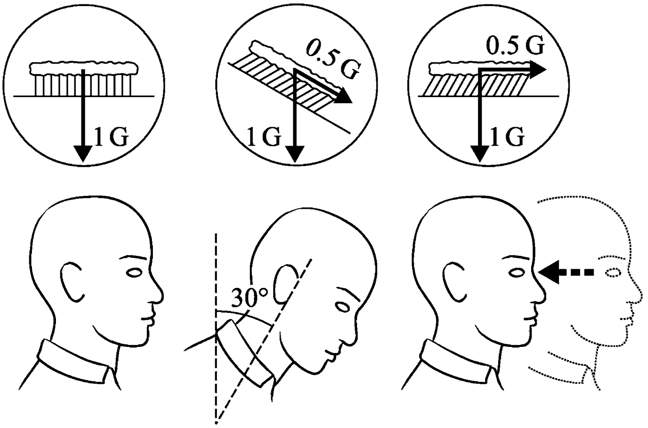

Figure 3.5. The Otoliths Bend the Hair Cells of the Utricles the Same Way When the Head Is Maintained at a Constant Tilt Angle of 30° Relative to Gravity and When the Whole Body in Translated Backwards at 0.5 g.

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[2] In a normal situation, the brain would easily distinguish between a tilt of the head relative to gravity and a head translation by comparing the sensory information from the otolith organs with that from the eyes or muscle proprioceptors. But in complete darkness, there could be a conflict between the proprioceptive input (e.g., signaling that the head is tilted) and the otolith input (e.g., signaling that the head translates).

On Earth, otolith signals can be interpreted as either linear motion (translation) or as tilt with respect to gravity. Because stimulation from gravity is absent in weightlessness, interpretation of otolith signals as tilt is inappropriate (Figure 3.6). Therefore, it is possible that during adaptation to weightlessness, the central nervous system reinterprets all otolith signals to indicate translation. This hypothesis is known as the Otolith Tilt-Translation Reinterpretation (OTTR). This central reinterpretation would persist following return to Earth, and be at the origin of spatial disorientation, until re-adaptation to the normal gravity environment occurs [Parker et al., 1985; Young et al., 1986].

Evidence for the OTTR hypothesis comes from subjective reports by astronauts returning from spaceflight who have a sense of body translation when they voluntarily pitch or roll their head. For example, many experience a backward translation when they pitch their head forward, or a rightward translation when they roll their head to the left. The utricle and the saccule are not located at the axis of head rotation during roll or pitch head movements. Therefore, this movement must evoke otolith stimulation, which could readily be perceived as translation during and immediately after landing. Such a misleading interpretation of otolith signals might be responsible for the staggering posture of the astronauts as soon as they land. The astronauts tend to lean to the outside of the turn when walking and turning corners immediately after landing, also suggesting a misevaluation of the apparent vertical from otolith signals.

The OTTR hypothesis has been the theoretical basis of much space research on the neuro-vestibular system for the past 15 years. I was fortunate enough to be able to perform a space experiment that tested this hypothesis in 1998. This experiment, which flew on board the Neurolab *STS-90* mission, used a human-rated centrifuge constructed by ESA [Buckey and Homick, 2003]. On Earth, when an individual is rotated in a centrifuge in darkness, he/she senses the direction of the resultant gravito-inertial force and regards this as the vertical. If a centrifugal force equivalent to 1 g is directed sideways, the gravito-inertial force is displaced 45° relative to the upright body, and the subject has a sense of being tilted by 45° to the outside (Figure 3.7). In microgravity, however, the gravitational component is negligible and the gravito-inertial force is equivalent to the centrifugal force. This force could be interpreted

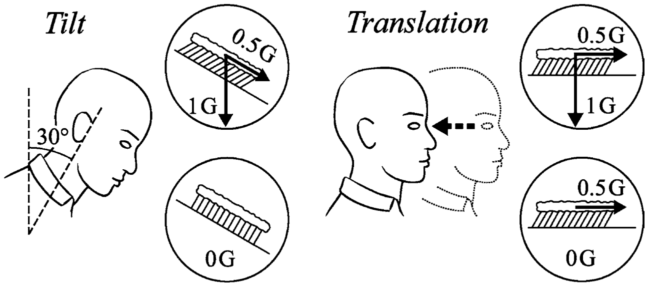

Figure 3.6. In Microgravity, the Otoliths Are Stimulated by Head Translation, but Not by Head Tilt. Consequently, It Is Hypothesized that, After a Period of Adaptation, the Brain Reinterprets All Otolith Signals as Signaling Head Translation. (Credit Philippe Tauzin).

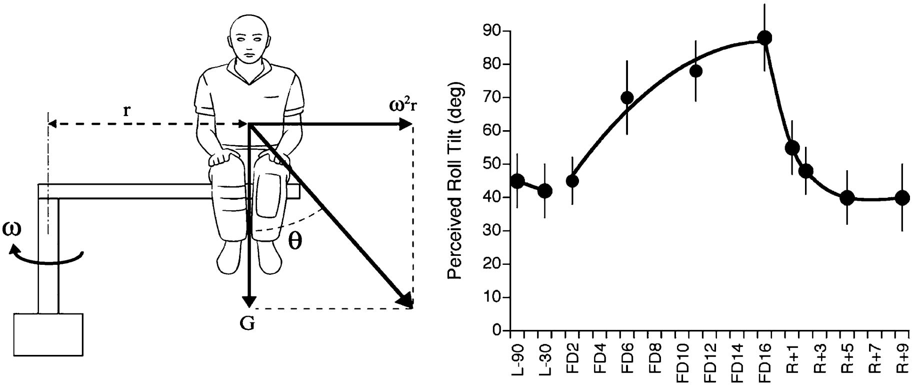

Figure 3.7. On Earth, a Subject Sitting at the End of a Centrifuge Arm in Darkness Adopts the Direction of the Gravito-Inertial Force (GIF) as the New Direction of "Gravity". In Microgravity, the GIF Is Equivalent to the Centrifugal Force and the Subject Could Perceive Either a Body Tilt or a Body Translation, Depending on the Interpretation of the Otolith Signals by the Central Nervous System.

either as a 90° tilt of the body, or a whole body translation in the opposite direction. During the Neurolab mission, four astronauts were asked to report their perceived angle of tilt during steady-state centrifugation in darkness throughout the flight and during the postflight re-adaptation period. Centrifugation was always perceived as tilt, not translation. Therefore the findings do not support the OTTR hypothesis. Despite the fact that the otoliths do not respond to head tilt in orbit, the brain continues to sense a steady-state linear acceleration applied to the otoliths as the upright in all circumstances.

The debate regarding the OTTR hypothesis is still raging. Some have proposed that the OTTR only occurs during voluntary head movements, or only during rotational head movements, or that OTTR must be frequency dependent. Centrifugation, by applying very low frequency passive linear acceleration to the entire body, would thus not elicit OTTR. I am currently conducting follow-up studies on astronauts returning from spaceflight, by spinning them about a tilted axis or tilting them in roll or in pitch while translating at various frequencies to further address this hypothesis.

The Neurolab centrifuge experiment, however, brought another interesting result. At the beginning of the flight, during a 1-g centrifugation in darkness, the astronauts perceived a 45° tilt to the side, very much like on Earth. However, as the mission progressed, they felt more and more tilted, until they felt a 90° tilt to the side on flight day 16 (Figure 3.7). This simple result indicates that the brain does not continuously calculate the direction of gravity, but uses an internal estimate of gravity whose weighting changes during spaceflight. The internal estimate normally used on Earth carries over to the early period of exposure to weightlessness, and therefore the astronauts continue to perceive a 45° tilt, despite the absence of sensed gravity. After a period of adaptation, the internal estimate declines to zero and the astronauts perceive a full body tilt to the side [Clément et al., 2001, 2003].

3.2.1.3. Changes in the vestibular receptors

Although it is difficult to measure changes in the vestibular end organs directly, several attempts have been made to examine the question "Is there anatomical and physiological changes in the vestibular end organs and their primary afferents after exposure to microgravity?"

Experiments on frogs have revealed no alteration of the sensory epithelium of the vestibular organ of adults returned from an 8-day stay aboard *Mir*, or following larval development in microgravity. However, changes in the structure of the otolith crystals in rats had been observed during an earlier *Cosmos-782* mission. A degeneration of the otolith crystals could occur because of changes in body calcium, protein metabolism, and calcium exchange. In addition, it is unclear how many of these changes were due to the high accelerations experienced by the animals during take-off and landing.

More recent Spacelab experiments indicated no deleterious effects in the otoliths of rodents who flew as compared with the ground controls. However, an unexpected change found during the Spacelab *SLS-1* mission, and later confirmed during the Neurolab mission, was an increase (by a factor of 12) in the number of synapses in hair cells from the in-flight maculae as compared with the control data. These findings suggest that mature utricular hair cells retain synaptic plasticity, permitting adaptation to an altered environment. Consistent with these results is data that show a decrease in synapse activity in centrifuged rats. These data suggest that the maculae adapt to g-forces changes in either direction by up- or down-regulation of synaptic contacts in an attempt to modulate neural inputs to the CNS [Ross and Tomko, 1998]. Recent morphometric studies of the utricular area performed in tadpoles following stays on board the ISS confirmed a vestibular sensitization in microgravity.

Primary afferent fibers of the vestibular nerve are relaying the information originating at the hair cells to the brainstem. Within each nerve are also efferent fibers from the CNS that provide neural feedback to modulate the activity of the peripheral organs. The resting activity of single otolith afferents and their response to centrifugal forces were found to be different in microgravity compared to the ground condition in frogs. Recently, a study recording the vestibular nerve impulse data from the oyster toadfish during the Neurolab mission confirmed these results. On the other hand, the spontaneous firing rate of single horizontal semicircular canals afferents did not change postflight relative to preflight in two flight monkeys. However, these monkeys were restrained in a laboratory chair, thus preventing any movements of the head during the flight. It is known that movement and interaction with the environment are necessary factors to drive adaptive changes. For example, vestibular patients show a faster recovery when moving around after vertigo crisis or unilateral surgery.

Few experiments addressing the early development of the vestibular system have been carried out in space. This is an interesting research topic given that in all species the vestibular system begins to respond to linear or angular acceleration prior to hatching or birth, in contrast to hearing or vision, which can be postnatal in some species. Mammalian offspring emerge from the birth canal in a species-typical orientation, which, for rats and humans, is headfirst. Fetuses typically achieve the appropriate orientation via active, in-utero behavior. Perhaps the vestibular system is employed for this early task. Indeed, many infants born in the breach position are born with vestibular disorders. Also, the so-called "righting response," by which the newborn mammals actively adjust from a supine to a prone position, is disrupted by induced vestibular disorders during development.

In the development of the visual system, activity in the retinal pathway influences the specification of those connections that determine how visual information is processed in the cerebral cortex. In every other sensory system known, especially those that make up the neural space maps in the brainstem, sensory stimulation has been implicated in the initial specifications of the connections and physiological properties of the constituent neurons. Only in the utricle and saccule gravitational pathway has it been impossible to study the role of sensory deprivation, because there is no way to deprive the system of gravitational stimulation on Earth. For this reason, experiments in microgravity should be planned to test the hypothesis that gravity itself plays a role in the development and maintenance of the components of the vestibular system. These components include both the vestibular receptors of gravity (i.e., the sensory hair cells in the utricle and saccule, vestibular ganglion cells that form synapses with vestibular hair cells, and vestibular nuclei neurons) and the motor neurons. The latter receive input from axons of the vestibular nucleus neurons composing the vestibular reflex pathways. The vestibular system also receives inputs from the proprioceptive system, involved in the control of muscle length and tension, and from the visual system, involved in the control of eye movements. Little is known about the exact nature of these interactions and virtually nothing concerning the development of these connections.

3.2.2. The other senses

In common speech, five different senses are usually recognized: sight (vision), hearing, taste, smell, and touch. Of these, the first four use special organs – the eye, ear, tongue, and nose, respectively, whereas the last uses nerve endings that are scattered everywhere on the surface of the body, as well as inside the body (visceral sensations). Proprioceptive sensations arise from organs within the body, from muscles, tendons, and joints. To what level these five senses are affected by spaceflight is uncertain.

3.2.2.1. Vision

The visual environment in space is altered in several ways. First, objects are brighter under solar illumination. Earth's atmosphere absorbs at least 15% of the incoming solar radiation. Water vapor, smog, and clouds can increase this absorption considerably. In general, this means that the level of illumination in which astronauts work during daylight is about one-fourth higher than on Earth. Second, there is no atmospheric scattering of light. This causes areas not under direct solar illumination to appear much darker (Figure 3.8).

Early anecdotal reports that orbiting astronauts were able to see objects such as ships, airplanes, and trucks with the naked eye suggested improved visual acuity in space. Extensive testing of Gemini astronauts was performed using a small, self-contained binocular optical device containing an array of high- and low contrast rectangles. Astronauts judged the orientation of each rectangle and indicated their response by punching holes in a record card. Another method, taking into account the particularity of the visual environment of space described above, also used large rectangular patterns displayed at ground sites in Texas and Australia. Astronauts were required to report the orientation of the rectangles. Displays were changed in orientation between passes and

Figure 3.8. An Astronaut Uses a Still Camera to Photograph a View of Earth from a Window in the Cupola of the ISS. (Credit NASA).

adjustments for size were made in accordance with slant range, solar elevation, and the visual performance of astronauts on preceding passes. Results with both measurement methods indicated that visual performance was neither degraded nor improved during spaceflight. The astronauts' reported ability to detect moving objects (airplanes and ships) was probably based on the detection of turbulence or waves behind the vehicles. Also, the color contrast might improve the ability to identify features, as Astronaut William Pogue described it during his *Skylab* mission "We were able to see icebergs about a hundred yards in diameter quite easily because of the higher contrast of white ice with the dark blue sea [Clément and Reschke, 1996]."

More refined visual testing has been performed on several shuttle flights using a specially-designed visual test apparatus to assess contrast sensitivity, phoria, eye dominance, flicker fusion frequency, stereopsis, and acuity (Figure 3.9). With the exception of reduced contrast sensitivity, no significant changes due to weightlessness were found. These changes were too small to impact operational performance. However, if contrast sensitivity continues to change during longer exposure to weightlessness, the decrement could become operationally significant.

An interesting observation is that some astronauts have described a decrease in their ability to see clearly at close range when in space. Interestingly enough, most of the astronauts experiencing this change were in their early forties and could see clearly without reading glasses when they were on the ground. One theory as to why this might happen is that the eye is like a water balloon. Rest it on a table and it gets longer as it flattens out (which is the normal condition on Earth). Put that balloon in space and it shortens, becoming more round. The eye could do the same thing and when it shortens it becomes farsighted, causing more difficulty seeing objects up close.

Recent studies revealed that optic disc edema, globe flattening, choroidal folds, hyperopic shifts, and raised intracranial pressure have been observed in approximately 20% of astronauts on long-duration missions both during and after spaceflight. In some cases, these changes were transient and in others, the changes were persistent with varying degrees of visual impairment. Furthermore, there are indications that

Figure 3.9. Near-Visual Acuity Test Performed by an Astronaut on Board the Space Shuttle. (Credit NASA).

visual alterations and changes to the eye (disc edema) have occurred in astronauts on space shuttle flights, but the condition is not well defined and lacks consistent data. These alterations could have profound mission impacts and long-term health impacts for the individual, such as a permanent loss of vision. One hypothesis for these changes is intracranial hypertension, due to the headward shift of body fluids following orbital insertion. Microgravity is known to produce a headward shift of 700–1,400 mL of fluid (see Chapter 4, Section 4.3.2). Photographic studies show a significant decrease in the size of the retinal vasculature after flight. Intraocular pressure rises during flight and drops below pre-flight levels after landing. The relationship between intracranial pressure and changes in visual acuity could also be due to excessive CO_2 exposure. Operational data from ISS and *Mir* is being mined and studies are planned to determine if there is indeed a relationship, but no definitive information is currently available.

It is also worth noting here that the light flashes perceived by the astronauts in the absence of normal visual stimulation were caused by heavy ionized cosmic particles passing through retinal cells (see Chapter 2, Section 2.5.2). Although no performance disturbance has been associated with these light flashes, it is likely that the flashes mask transient visual stimuli.

Many astronauts have reported impairment in evaluating distances, both on the Moon[3] and during orbital flights. The collision of the *Progres*s spacecraft with the *Mir*

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[3] The following quotes are exerted from the postflight debriefings of the astronauts who walked on the Moon during the *Apollo-12* mission [Godwin, 1999]:

"Everything looked a lot smaller and closer together in the air than it turned out to be on the ground. When we were on the ground, things that were far away looked a lot closer than they really were. The thing that confused me was that we were so close to the Surveyor crater. I didn't realize we were as close to it as we were." —Pete Conrad.

station in 1996 could have been due to a misevaluation by the *Mir* cosmonauts of the actual distance between the two vehicles. I have a personal interpretation for these changes in distance perception [Clément and Reschke, 2008]. I think that perception of absolute distances is altered after a long exposure in a confined environment where there is only a short distance sighting. It is known that distances between objects and the observer are altered when there are no objects with familiar sizes, such as trees, people, or vehicles, in the background. This is the case on the Moon, inside a space vehicle, or any other confined place. People who spend a long time in enclosed chambers, such as divers or submariners, have trouble evaluating distance when they get out. For this reason, submarine crewmembers are not allowed to drive immediately after returning from long tour of duty in the confined space of a submarine.

The objects seen inside the ISS are within distances of several cm to a few meters, whereas the objects outside (Earth or the stars) are very far away. There is no intermediate distance range. It is therefore possible that the perception of the distances to objects is altered in this intermediate range.

Even when objects of a familiar size are present, our perception of distances is different when we look in the vertical direction. For example, when we look down from the top of a 100-m tall building, the people and the vehicles below look noticeably small. But when we look 100 m "down" the street at ground level, we don't comment on how small the people and vehicles look. The reason is that we have learned the "rules" for scaling people at a distance, but not from a height. In the absence of a vertical gravitational reference, the perception of distance might be distorted in the same way as when we look down or up [Clément and Reschke, 2008].

An experiment currently in progress on board the ISS seems to indicate that the astronauts underestimate distance for the intermediate range of 100–1,000 m (Figure 3.10). Also, the perception of distance in the vertical direction, which is clearly overestimated on the ground (e.g., when on top of a building, the people in the streets look small), become as accurate as in the horizontal direction after 1 month in orbit. It is unclear if these illusions are direct effects of reduced gravity on the neuro-vestibular system, as seen in vestibular patients on Earth [Clément et al., 2008b, 2009] or due to other factors of the space environment, such as high contrast, confinement to cramped quarters, and the absence of known landmarks in the crewmember's intermediate space. Nevertheless, these errors in visual perception and misperceptions of size, distance and shape could represent potentially serious problems. For example if a crewmember does not accurately gauge the distance of a target, such as a docking port or an approaching vehicle, then the speed of this target could also be misevaluated. In addition, disturbances in the mental representation of objects and the surround may influence the ability of astronauts to accurately perform perceptual-motor and perceptual-cognitive tasks such as those involved in robotic control.

"In appearances, it took us a long time to convince ourselves that some of the craters which looked so close were really much farther away." —Alan Bean.

"When we were at the ALSEP site, it looked as if we were about 450 feet west and 50 feet north of the position of the LM. It was a pretty good level site. Later when I got back to the LM and looked back, I noticed it didn't look as if the site were that far away. This was the continual problem we had, trying to judge distances." —Alan Bean.

Figure 3.10. ESA Astronauts During a Training Session for the 3D-SPACE Experiment. This ISS Experiment Uses a Head-Mounted Visual Display, a Trackball, and a Digitizing Tablet. The Subject Is Presented with Depth-Related Visual Illusions, or 3D Objects That He Can Adjust So That They Look “Normal”, or Natural Scenes in Which He Has to Judge the Distance Between Identified Landmarks. The Digitizing Tablet Is Used for Neuropsychological Testing of Writing Horizontally and Vertically and Drawing Geometrical Figures with the Eyes Closed. (Credit ESA).

Suspicions are that daylight is not bright on the surface Mars. The sunlight on Mars is about one-half of the brightness of that seen on Earth. The sky of the Red Planet does not appear blue, but pink due to suspended dust, which means that the surface of Mars is, in fact, darker than what is experienced on Earth [Online source: http://quest.arc.nasa.gov/mars/ask/atmosphere/].

Also, on Mars, the terrain may be more sloped than that explored by the *Apollo* astronauts. The astronauts may be traversing areas of deep shadow, possibly requiring the use of lights. Scientists are also investigating options for EVA sensory supplementation. Although vibrotactile and electrodermal cueing systems have been demonstrated in patients, these techniques appear encumbering and impractical, and require that the suit also incorporate a capable inertial attitude and heading reference system. Night vision sensor imagery, an artificial horizon, and a navigation display could also be incorporated into an add-on external heads-up display [Hirmer and Clément, 2011].

3.2.2.2. Hearing

“In space, no one can hear you [scream].” This cliché, which is commonly used in science fiction movies, has apparently not attracted the interest of scientists for studying hearing during spaceflight, since very little data is available yet.

The ISS is a noisy place. To better characterize the acoustic environment, a sound measurement survey is performed once every 2 months to measure the acoustic spectral levels at specified locations. An acoustic engineering evaluation is performed to diagnose acoustic abnormalities, investigate crew complaints, and evaluate effectiveness of newly installed noise reduction measures. Noise exposure levels are measured by crew-worn dosimeters complemented by dosimeters deployed at fixed locations to determine work, sleep, and 24-h noise exposure levels (with a microphone on the shirt collar). Recent data indicate that noise levels on the ISS, even during sleep periods, can average more than 70 dBA,[4] and that the recordings have "maxed out" at over 90 dBA during scheduled sleep intervals.

Several aspects of spaceflight can have an impact on hearing capability: (a) life support equipment is continuously running (ranging from 64 dBA for the air conditioning to 100 dBA for some vent relief valves) and the noise reverberates through the spacecraft's structure; (b) astronauts spend 24-h a day in the office, always close to noise sources; and (c) there is no privacy, with a constant interaction with other crewmembers. Thus quietness periods such as on Earth do not exist: earplugs can reduce noise but not vibrations.

Spaceflight raises a spectrum of noise questions: its effect on perception and performance, adaptation effects, the fatiguing and annoying aspects of noise, and individual sensitivity differences. The degree to which noise and environmental disturbances affect sleep during spaceflight missions remains to be determined. Because certain minimum noise levels are always present, spaceflight potentially constitutes a more stressful noise environment than a simple consideration of decibel levels would imply (Figure 3.11).

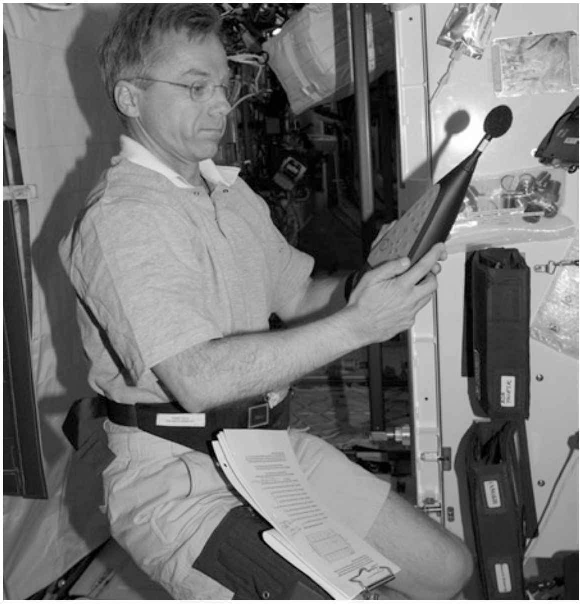

Figure 3.11. Canadian Space Agency Astronaut Robert Thirsk Works with a Sound Level Meter for an Acoustic Survey in the Destiny Laboratory of the ISS. Note the Procedure Documents on His Lap. (Credit NASA).

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[4] The threshold for hearing is defined as 0 dBA, corresponding to corresponds to 0.00000003% of atmospheric pressure (1/30 billionth). The threshold for pain is 0.03% of atmospheric pressure, or approximately 120 dBA. For comparison, a circular saw creates noise levels from 91 to 99 dBA. Even what we call "silence" on Earth is in fact a background noise of about 40 dBA.

Although very stringent noise requirements for ISS result in a noise environment comparable to home and office, intelligibility of hearing as noise increases may vary across individuals. For example, it is known that both the lack of language proficiency and the reverberance in a room impair hearing. The performance of a native English speaker on board the ISS at 60 dBA therefore must to be compared with that of a non-native English speaker at 68 dBA! In addition, low noise levels can also be annoying and affect individual and group (communication) behavior.

The investigation of hearing in astronauts is difficult to conduct during spaceflight because classical hearing assessment techniques do not work in the noisy environments often found in spacecraft (no soundproof laboratory). Because crewmembers are at risk for hearing loss due to noise levels often encountered during spaceflight, techniques and investigation to track this loss are needed during and after the mission.

Auditory brain stem response recordings were investigated during shuttle flights. No significant differences were observed between mean latency values for any potential on the ground or during flight, suggesting that the auditory function is not altered in microgravity [Thornton et al., 1985]. Another experiment performed on *Mir* showed that the localization of a sound source in microgravity was within the same range as on Earth, i.e., between 1° and 2°. Since the faculty of localizing sound sources depends on normal binaural hearing, it was concluded from this study that hearing was not altered in cosmonauts.

3.2.2.3. Smell and taste

It is well known that during spaceflight, astronauts ask for more spices and condiments to add taste to the prepared food. Diminished sensitivity to taste and odor could result from the passive nasal congestion reported in conjunction with the headward shift of fluid. Taste, particularly the non-volatile component mediated by the taste buds, may be susceptible to threshold shifts in microgravity, because of a reduced mechanical stimulation as a result of changes in the convection process.

Evaluation of olfactory recognition using paper impregnated with lemon, mint, vanilla, or distilled water, and taste recognition using solution of solutions of sucrose, urea, sodium chloride, and citric acid, demonstrated no subjective changes in smell or taste function postflight. However, there were large differences among individuals. Some of them could have been due to the reminiscence of space motion sickness symptoms!

Materials used in spaceflight are subjected to testing for odor as well as for flammability and toxicity. Odor evaluations are made by panels of test subjects who rate materials on a scale from 0 (undetectable) to 4 (irritating) with a score of 2.5 (falling between "easily detectable" and "offensive") considered as passing. Nevertheless, because particulate matter does not settle out in weightlessness, odor problems in a space habitat may be more severe than under similar terrestrial conditions.[5]

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[5] An astronaut onboard the ISS reported: "I had the pleasure of operating the airlock for two of my crewmates while they went on several space walks. Each time, when I repressed the airlock, opened the hatch and welcomed two tired workers inside, a peculiar odor tickled my olfactory senses. At first I couldn't quite place it. It must have come from the air ducts that re-pressed the compartment. Then I noticed that this smell was on their suit, helmet, gloves, and tools. […] The best description I can come up with is metallic, a rather pleasant sweet metallic sensation. It reminded me of my college summers where I labored for many hours with an arc-welding torch repairing heavy equipment for a small logging outfit. It reminded me of pleasant sweet smelling welding fumes. That is the smell of space" [Pettit, 2003].

Also, responses to odors can be accentuated by the presence of visual cues. For example, during the earlier Spacelab missions, crewmembers complained of disturbing odors, which they attributed to the primates and test rats which shared their facilities and which were in view [Connors et al., 1985]. In later missions, the animal cages were placed in visually separated areas and no odor problems were mentioned.

3.2.2.4. Proprioception

The absence of gravity modifies the stimuli associated with proprioception and impact spatial orientation, including knowledge of position in the passive limb, difficulty of pointing accurately at targets during voluntary limb movement, modification of tactile sensitivity, and changes in the perception of mass. However, the nature of proprioceptive changes in microgravity has been poorly studied. There is almost no space study of neck and joint angle sensors, and on the role of localized tactile cues in the perception of body verticality.

When crewmembers point at remembered target positions with their eyes closed, they make considerable errors and tend to point low. When they are asked to reproduce from memory the different positions of a handle, the accuracy of setting the handle to a given position is significantly lower with an error towards a decrease of handle deflection angle. Also, when trying to touch various body parts, they usually note that their arms are not exactly where expected when vision is restored. The problem is that these examples are suggestive of either degradation in proprioceptive function, or an inaccurate external spatial map, or both [Watt, 1997; Young, 1993].

An elegant way to evaluate changes in the proprioceptive function is to measure the subjective sensation generated by the stimulation of proprioceptive receptors. A classic technique consists in vibrating a muscle tendon to elicit illusory limb movement. Using this technique, it was observed that the illusion of body tilt forward or backward was less pronounced in-flight than postflight during vibration of lower leg muscles. One interpretation of this result is that the utricles and saccules are unloaded in microgravity and decrease their descending modulation of alpha and gamma motoneurons, resulting in decreased tonic vibration reflexes.

A nice illustration of an alteration of proprioceptive inputs during the early exposure to microgravity is the impossibility for an astronaut to maintain a “vertical” posture, perpendicular to the foot support, in absence of visual information (Figure 3.12). The large body tilt observed in these conditions reveals an inaccuracy in the proprioceptive signals from the ankle joint (or in their central interpretation). After flight day three, however, the astronauts are able to maintain an upright posture, suggesting that adaptive processes take place quite rapidly [Clément and Lestienne, 1988].

Among the somato-sensory systems projecting to the neuro-vestibular system, the position receptors of the cervical column (neck receptors) play an important role. During the Spacelab-*D1* mission, the trunk of a crewmember was passively bent sidewards or forwards, while keeping his head fixed to the floor of Spacelab, thus stimulating the neck receptors. The crewmember reported an illusory rotation of a head-fixed target cross seen in the monitor of his helmet, which was entirely due to the stimulation of the cervical position receptors, since the otoliths were not stimulated.

Another interesting feature of microgravity is that it allows separation between two distinct physical concepts, mass and weight, which both produce similar sensations of heaviness. On Earth, weight can be judged passively through the pressure receptors in

Figure 3.12. An Astronaut with the Feet Attached to the Floor of the Space Shuttle and Placed in Darkness Using an Occluding Goggle Is Instructed to Maintain an "Upright" Posture on Flight Day Two. In the Absence of Gravitational and Visual Inputs, His Body Is Tilted Forward, Suggesting a Recalibration of the Proprioceptive Inputs from the Ankle Joint. (Credit NASA).

the skin, if the object is placed upon a supported limb. Weight can also be judged actively, if the object is held against the force of gravity by the muscular effort, or is repeatedly lifted. Mass can only be judged actively, derived from the force required to produce a given acceleration, or from the acceleration produced by imparting a given force. Thus, active weight perception usually includes mass perception. It is therefore difficult to investigate weight without mass during active movement, except in weightlessness. Using balls of various masses that the astronauts shook up and down moving their arms, it was found that the process of discriminating the mass of objects in microgravity was less accurate than in normal gravity. Weight discrimination was impaired for 2 or 3 days postflight, while crewmembers felt their bodies and other objects to be extra heavy. The impairment in-flight was partly due to the loss of weight information (a reduction in the pressure stimulation), and probably also to incomplete adaptation to microgravity. The increase in apparent heaviness of objects reported for static weight judgment after the flight suggests that some central re-scaling of the static pressure systems had occurred [Ross et al., 1986].

3.3. Posture and movement

Postural activity is the complex result of integrated orientation and motion information from visual, vestibular, and somato-sensory inputs. These inputs collectively contribute to a sense of body orientation and, additionally, coordinate body muscle activities that are largely automatic and independent of conscious perception and voluntary control.

3.3.1. Rest posture

Human factor studies, after investigating photographs taken during *Skylab* missions, have led to the Neutral Body Posture model (Figure 3.13). This model is characterized by a forward tilt of the head (with the line of sight 25° lower than the body-centered horizontal reference), shoulders up (like a shrug), and arms afloat, up and forward with hands chest high.

Recent investigations, taking into account body size, gender, and mission duration suggest, however, that the neutral body posture model is too generalized, and should be modified with additional data to provide more representative spaceflight crew postures. However, it is unclear how the direction of the line of sight has been evaluated from the *Skylab* photographs. Also, the downward deviation of gaze in microgravity in this model is in contradiction with the results of several space experiments that actually measured the eye deviation during spaceflight (see Section 3.3.5).

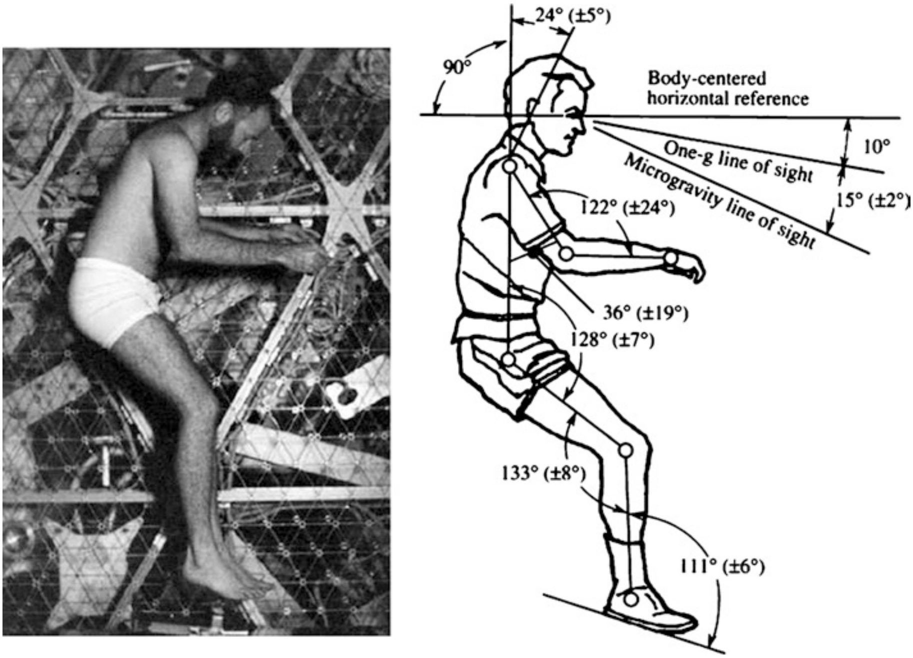

Figure 3.13. The Neutral Body Posture and the Rest Position of Foot, Leg, Hip, Elbow, Shoulder, and Neck Joints in Microgravity, as Well as the Direction of the Line of Sight, Were Modeled Based on the Photographs of Skylab Astronauts. (Adapted from NASA [1995]. Credit NASA).

3.3.2. Vestibulo-spinal reflexes

Two of the more dramatic responses to orbital flight have been postural disturbances and modified reflex activity in the major weight-bearing muscles. For example, monitoring the Hoffman reflex (or H-reflex), which takes advantage of the anatomical pathways that link the otoliths and spinal motoneurons, has been selected as a method of monosynaptic spinal reflex testing to assess otolith-induced changes in postural muscles. In contrast to a doctor tapping a patient's knee to produce the proverbial "knee jerk" reflex, during H-reflex the stimulus is an electrical shock to sensory fibers coming from stretch receptors in the calf (*Soleus*) muscle, and the response is the electrical activity recorded from the muscle. Each time a subject is tested, the number of motoneurons that have been excited by a standard volley of sensory impulses is counted. That number is an indicator of spinal cord excitability. Interestingly enough, this number fell in ISS crewmembers, quite quickly at first and then more gradually over many days. A return to normal was observed within days after landing [Watt, 2001].

When performed in conjunction with linear acceleration, such as "falls" simulated by bungee cords, the H-reflex amplitude is low in-flight, but very large postflight. Interestingly, sudden drops are perceived as falls or drops on Earth, and were felt in-flight much as they were preflight. Later in-flight as well as postflight drops were perceived as more sudden, fast, and hard. During those drops, the subjects did not have a falling sensation, but rather a feeling that "the floor came up to meet them".

Second, extensive dynamic postural testing with a moving platform was performed before and after space missions. Balance control performance has been systematically tested before and after the flight using a computerized dynamic posturography system widely employed for evaluation of balance disorders [Paloski et al., 1993]. This system consists of a platform and a visual surround scene, both of which are motorized to simulate motion. Subjects complete multiple tests before and after the flight to establish stable individual performance levels and the time required recovering them. Two balance control performance tests are administered. The first test examines the subject's responses to sudden, balance-threatening movements of the platform. Computer-controlled platform motors produce sequences of rotations (toes-up and toes-down) and translations (backward and forward) to perturb the subject's balance. The second test examines the subject's ability to stay upright when visual or ankle muscle and joint information is modified mechanically (Figure 3.14).

Postflight measurements revealed significant deviations from the results obtained before flight. The strategy used by the individuals for balancing on the moving platform is modified, and their behavior indicates a decrease in their awareness of the direction and magnitude of the motion. On landing day, every subject exhibited a substantial decrease in postural stability. Some had clinically abnormal scores, being below the normative population 5th percentile. After flights ranging from 5 to 13 days, postflight re-adaptation took place in about 8 days and could be modeled as a double-exponential process, with an initial rapid phase lasting about 2.7 h, and a secondary slower phase lasting about 100 h. The effects of demographic factors like age, gender, and longer mission duration on these responses are currently being evaluated.

Information obtained from these investigations is promising for ground-based clinical research. A relatively large number of individuals on Earth suffer from prolonged, frequently life-long, clinical balance disorders. Disorders like Ménière's disease and

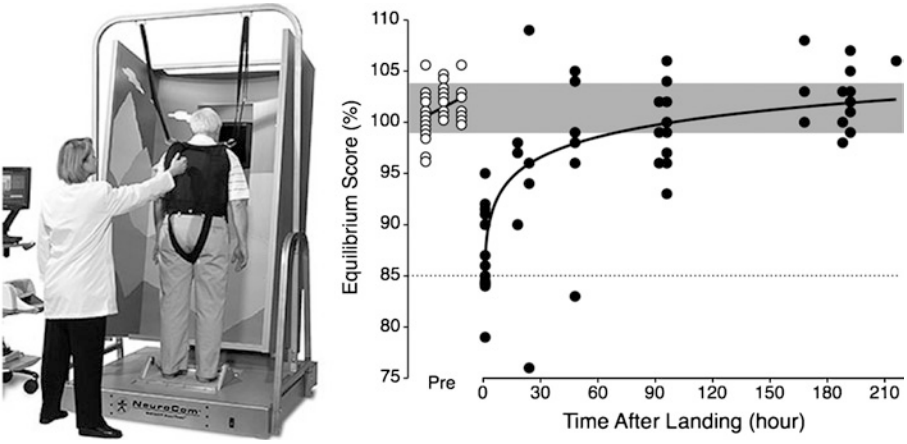

Figure 3.14. Subjects' Ability to Stand as Still as Possible Is Investigated Using a Computerized Force Platform Inside a Visual Booth. The Platform and the Booth Are Designed to Isolate the Multiple Sensory Information Used in Balance – Visual, Vestibular, and Proprioceptive. An Equilibrium Score Is Calculated from Various Sensory Tests, E.g., with the Eyes Open or Closed, the Platform Still or Translating, the Visual Environment Still or Tilting. The Graph Compares the Data for 13 Crewmembers Before (Pre) and After Landing (in Hours Following Shuttle Wheel Stop), Compared with a Large Normative Database. A Few Hours After Landing, the Average Returning Crewmember Was Below the Limit of Clinical Normality (*Dashed Line*). Preflight Stability Levels Were Achieved by 8 Days After Landing, Following a Double Exponential Time Course. (Adapted from Paloski et al. [1993]).

traumatic injuries to the inner ear can severely influence quality of life. Falls are the leading cause of injury-related deaths in the elderly and these numbers continue to increase. Inner ear disorders are thought to account for 10–50% of falls among senior citizens. Currently, human spaceflight is the only means available for studying the response to sustained loss and recovery of inner ear information. Comparison between data from astronaut-subjects and similar data from patients and elderly subjects demonstrates similarities between these balance disorders. One sensible difference is that the posture problems recover in a few days for the astronauts, whereas it can take weeks in the patients, some of who never recover. It is hoped that a better understanding of the strategies used during the recovery process in the astronauts, and of the plasticity of this system in general, will help to improve rehabilitation treatments for patients with balance disorders on Earth.

3.3.3. Locomotion

The cautious gait of astronauts descending the stairs of the "white room" docked with the space shuttle and walking on the runway[6] is an obvious example of changes in

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[6] The ritual of the crew walking on the runway and inspecting the vehicle immediately after landing is called a "walk-around" in NASA jargon. While the astronauts are "kicking the tires," the scientists are impatiently waiting to collect postflight data in the Flight Clinic. It is well known that re-adaptation to Earth gravity is very rapid and the possibility of testing this process at its earlier stage is fundamental for a full understanding of its mechanisms.

sensory-motor coordination. Typically, locomotion in microgravity poses no problem and is quickly learned. However, adaptation continues for about a month. The astronauts who pay a short visit to the ISS note that the long-duration crewmembers move more gracefully, with no unnecessary motion. They can hover freely in front of a display while the new comers would be constantly touching something to hold their position.

When locomoting in space, the astronauts stop using their legs. Instead they use their arms or fingers to push or pull themselves. For clean one-directional movements, a push must be applied through the center of gravity, i.e., just above the hips for a stretched-out body. When translating though, the natural place for the arms is overhead to grab onto and push off from things as they come whizzing by. This is the worst possible place from the physics of pushing and pulling for clean movements, for by exerting forces with arms overhead, some unwanted rotations will inevitably occur, which must be compensated with ever more pushes and pulls, giving an awkward look to the whole movement. "To cleanly translate, the best is to keep the hands by the hips when exerting forces and boldly go headfirst. This way the pushing and pulling is directed through the body's center of gravity and gives nice controlled motions without unwanted rotations." [Pettit, 2003].

Movement in a weightless environment obeys to the Newton's laws of motion. Friction forces are negligible and the angular momentum is always conserved unless acted on by an outside torque. Filmed sequences of astronauts performing a number of gymnastic moves in space were analyzed frame-by-frame. The principle of conservation of angular momentum was demonstrated as the astronauts tumbled, twisted and rotated in space. Throughout their motion and up until they entered in contact with the wall, the angular momentum was constant at 35.7 ± 1.2 kg × m^2/s while rotating freely.[7]

Since legs are used less for locomotion, new sensory-motor strategies emerge in microgravity. Some of this newly developed sensory-motor program "carries over" to the postflight period, which leads to postural and gait instabilities upon return to Earth. Both U.S. astronauts and Russian cosmonauts have reported these instabilities even after short-duration (5–10 days) spaceflights. Subjects experienced a turning sensation while attempting to walk a straight path, encountered sudden loss of postural stability especially when rounding corners, perceived exaggerated pitch and rolling head movements while walking, and experienced sudden loss of orientation in unstructured visual environments. In addition, oscillopsia and disorienting illusions of self-motion and surround-motion occurred during head movement induced by locomotion.

The beginning of the stance phase of locomotion, when initial foot-ground contact occurs, is characterized by a rapid deceleration of the foot. The forces created by the heel strike impact travel through the body and reach the head. The head-neck-eye complex then operates to minimize angular deviations in gaze during locomotion

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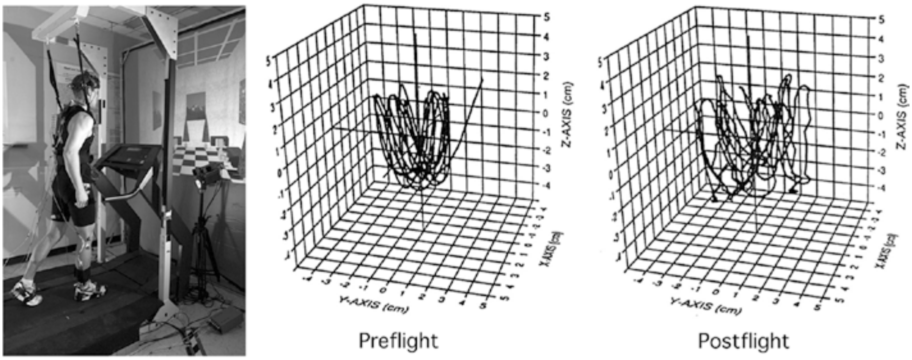
[7] Dan Barry, an astronaut of the *STS-96* Shuttle mission, got stranded in the middle of an ISS module, with the help of two fellow crewmembers. He then tried to kick himself over to the wall. He recalled later: "When I reached out an arm, my body moved back and my center remained in the middle of the room. I instinctively tried moving fast, then slow, and then bicycled my legs. None of it helped. I just had to wait for the air currents to drift me to the wall. Sneezing and spitting didn't do much good either. On the other hand, throwing clothing as fast as I could produced enough reaction to send me to the opposite wall.

[Pozzo et al., 1990]. After spaceflight, however, changes have been documented in both head-trunk and lower limb patterns of coordination. Bloomberg et al. [1997] reported changes in head pitch variability, a reduction of coherence between the trunk and compensatory pitch head movements, and self reports from crewmembers that indicated an increased incidence of oscillopsia (the illusion of a visual surround motion) during postflight treadmill walking (Figure 3.15). A number of characteristics of walking also appear to be changed after spaceflight. For example, during the contact phase of walking, the foot "thrusts" onto the support surface with a greater force than that observed before flight.

The alterations in locomotion seen after spaceflight raise some concern about the crew capability for unaided egress from the *space shuttle* or the *Soyuz* in a case of emergency. As discussed earlier, many crewmembers experience marked vertigo when making head movements during re-entry, landing, and afterwards. This vertigo could be a major obstacle to successful egress if vision were impaired, as with a smoke-filled cabin. An interesting investigation was performed by Bloomberg et al. [1999], in which the ability for crewmembers to repeat a previously seen trajectory without vision was examined. When attempting to walk a triangular path after flight, blindfolded subjects showed both under- and over-estimations of the distances walked, but a correct estimation of the angle turned. These results suggest a difficulty for reconstructing motion cues from the otoliths, but not from the semicircular canals. However, the changes found could also be related to the lower walking velocity during postflight testing. These results imply that mechanisms like computing self-displacement and updating spatial information (both of which being also called navigation) are disturbed by spaceflight and have to be reacquired after return to Earth.

Apollo astronauts fell frequently on the surface of the Moon. In particular, the high and rearward center of gravity of the Apollo suit influenced upslope walking, and the stiffness of the inflated suit strongly influenced gait, and made it impossible to squat to retrieve dropped objects. New requirements for suit center of gravity and biomechanical properties of various motions on the Martian surface must be defined.



Preflight

Postflight

Figure 3.15. Head Movements Along the Fore-Aft (*X*), Lateral (*Y*), and Vertical (*Z*) Directions in One Crewmember During Walking on a Treadmill Before Spaceflight and on the Day Following Landing of the Space Shuttle. (Adapted from Bloomberg et al. [1999]).

It is highly desirable to reduce the incidence of falls not only to reduce the residual medical risks, but also because falls cut into EVA efficiency, and regaining one's feet requires physical effort. Once tired, an astronaut might be expected to fall more frequently – a phenomenon very familiar to any beginner skier. Preflight sensorimotor locomotion training might help to expand the repertoire of automatic motor responses to locomotor disturbances [Paloski et al., 2008].

3.3.4. Body movement

On Earth's surface, gravity significantly affects most of our motor behavior. It has been estimated that about 60% of our musculature is devoted to opposing gravity. For example, when making limb movements during static balance, anticipatory innervations of leg muscles compensate for the impending reaction torques and the changes in location and projection of the center of mass associated with these movements. Similar patterns of anticipatory compensations are seen in-flight, although they are functionally unnecessary. Also, rapidly bending the trunk forward and backward at the waist is accompanied on Earth by backward and forward displacements of hips and knees to maintain balance. The same compensatory movements of hips and knees are made in weightlessness. Because the effective gravity torques are absent during spaceflight, the innervations necessary to achieve these synergies in weightlessness are different from those needed on Earth. Consequently, these in-flight movements must reflect reorganized patterns of muscle activation.

During the first space experiments in which I participated in 1982, which were conducted on board the *Salyut-7* space station, we found that dorsi-flexor muscles, e.g., the *Tibialis anterior* leg muscle, assume a larger role in space than on Earth in regulating the orientation of the individual relative to his/her support. This is in contrast with the general use of muscle extensors on Earth, which are used to counteract gravity. This transfer of motor strategies from one muscle group to another explains the forward tilted posture of crewmembers placed in darkness when instructed to maintain a posture perpendicular to the foot support (see Figure 3.12).

Using a simple ball catching experiment in weightlessness, it has been elegantly shown that the central nervous system uses an internal estimate of gravity in the planning and execution of movements. During the act of catching a ball on Earth, the brain estimates the trajectory of the ball, accurately taking into account its downward acceleration due to gravity. In space, a seated astronaut was required to catch a ball traveling at a constant velocity, in contrast to the constant acceleration that would occur on Earth (Figure 3.16). The ability to anticipate and predict is one of the nervous system's basic functions. When we catch a ball, the brain does not wait for it to touch the hand before stimulating arm flexor muscle contraction to compensate for the impact. About one third of a second before impact, the brain elicits just the right amount of contraction to counteract the force exerted, which itself depends on the weight of the object combined with the acceleration of its fall. The experiment led to the conclusion that the brain works by anticipating the effects of gravity on the ball rather than by making direct measurements of its acceleration. This anticipation ability remains even in conditions of weightlessness. Thanks to childhood experience, the brain possesses internal models of the gravity laws governing the behavior of a falling object, and perhaps more generally, Newton's law of mechanics. We see here the beginnings of

Figure 3.16. Ball Catching Experiment During the Neurolab STS-90 Mission. A Ball Was Thrown at the Subject at a Constant Velocity. The Trajectory of the Subject's Arm and the Activity of His Forearm Muscles Were Recorded as He Was Trying to Catch the Ball. (Credit NASA).

an adaptation to new laws. A longer period in weightless flight would now be needed to assess how such an adaptation might develop [McIntyre et al., 2001].

Likewise, the analysis of astronauts' writing or drawing showed that such fine movements are not altered in microgravity. When cosmonauts were asked to draw "horizontal" ellipses in the air without the aid of vision, results indicated minimal changes as a function of microgravity, suggesting that the body (egocentric) reference system was not disturbed. The subjects were capable of maintaining a sense of verticality despite disappearance of the main factor contributing to verticality on Earth, i.e., the gravitational force [Gurfinkel et al., 1993]. However, bending the head over the trunk causes the cosmonauts arm movement pattern to be more aligned with the head vertical axis, indicating that the head axis could also be used as a reference frame.

3.3.5. Eye movement

Eye movement is probably the response of the vestibular system that has been the most studied during spaceflight. For several decades, the study of eye movements has been a source of valuable information to both basic scientists and clinicians. The singular value of studying eye movements stems from the fact that they are restricted to rotations in three planes and the eyeball offers very little inertia to the eye. This facilitates accurate measurement (for example using video eye recording in near infrared light), a prerequisite for quantitative analysis.

Eye movements must continuously compensate for head movements so that the image of the world is held fairly steady on the retina, and thus appears clear and stationary. During head movements, the vestibular apparatus measures head velocity and relays this information to those centers controlling eye position to generate compensatory eye movements; this reflex behavior ensures that vision is not blurred. When performed in darkness, this leads to a pattern of rhythmic eye movements known as nystagmus, consisting of slow phases in the direction opposite to the head and fast phases that bring the eye back when it reaches the extreme of its travel. The nystagmus response to a rapid head movement outlasts the changes in signals in the semicircular canals, through the activation of a velocity storage mechanism located in the brainstem.

This so-called "vestibulo-ocular reflex" has been studied systematically in orbital flight, both during active (voluntary) and passive movements of the head [Clément, 1998]. With my co-investigators, we were the first to report that the amplitude of vertical eye movements was decreased during the first 3 days of weightlessness compared to normal value on Earth, but not the horizontal eye movements. In this experiment, the eye movements of an astronaut were recorded when he voluntary moved his head while either fixating a visual target or imagining that target in darkness. During the first few days in orbit, the vestibulo-ocular reflex was less efficient in stabilizing the visual image. This response recovered quickly, but subsequent investigations confirmed that after spaceflight, the pattern of eye and head movements was again significantly altered when subjects moved their head in an attempt to fixate a visual target (Figure 3.17).

Problems in hand-eye coordination and blurriness of the visual scene when re-entering in normal gravity have also been reported after long-duration missions. Tracking of moving visual targets seems to be altered, especially in the vertical direction. After landing, subjects have difficulties following a vertically moving visual dot. When the target moves up, the eyes try to catch-up the visual target with fast saccades rather than smooth pursuit. The vestibular nuclei located in the brain stem are part of a system that allows one to fix the gaze on a stationary target during voluntary head motions as well as to track moving targets. This system appears to be disturbed during spaceflight, presumably as a consequence of altered vestibular receptor function due to the absence of gravity. These deficits might pose a problem for piloting tasks during landing on Mars.

One problem in studying eye movements by asking subjects to perform voluntary head movements is that the CNS is "aware" of the movement to be performed. A copy of the motor command (the so-called efference copy) is presumably sent to the eye-head coordination control system, and this helps to achieve the adequate, compensatory eye movements. For this reason, scientists also use passive rotation generated by servo-controlled rotating chair or sled to generate unpredictable inertial stimulation of the vestibular system and to study the resulting responses. Several of these devices have flown on board the Spacelab. In 1985, a 4-m linear sled generated sinusoidal oscillations in subjects sitting either facing the track, or perpendicular to it, or lying

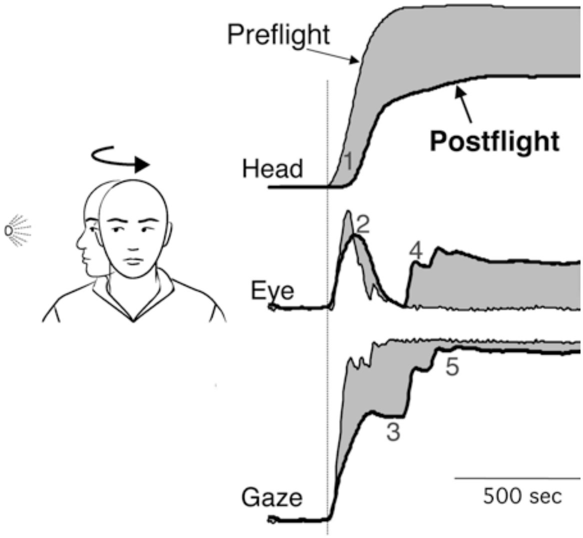


Figure 3.17. The Ability to Maintain Visual Fixation on Targets While Turning the Head Is Diminished Immediately After Landing. Compared with the Preflight Response, the Head Movement Is Delayed and Its Amplitude Is Reduced Postflight (1). As a Consequence, the Vestibulo-Ocular Reflex Is Initiated at an Inappropriate Time (2), Pulling Gaze from Target (3). Large Eye Saccades (4) Are Then Required to Direct Gaze Back on Target (5).

on their back. The peak linear acceleration was 0.2 g. Absolute thresholds for the perception of linear acceleration in-flight and postflight were found to be elevated in some astronauts and lowered in others for some axes, relative to ground-based controls. Another measure of linear acceleration sensitivity, the time elapsed from acceleration onset to reports of self-motion, which varies inversely with magnitude of acceleration, have been more consistent. Results indicate an elevation of the sensitivity when linear accelerations are exerted along the body longitudinal axis, and a decrease in sensitivity for the other axes. It is, however, difficult to rule out a contribution of the somato-sensory sensation in these results.

In 1992, a rotating chair flew on board the Spacelab *IML-1* mission, allowing the evaluation of the vestibulo-ocular reflex evoked by passive rotation of four crewmembers about the yaw, or pitch or roll axis, during the course of a 7-day spaceflight. Results showed that the responses generated by rotation in pitch and roll were the most affected in space.

More recently, in 1998, a human-rated centrifuge flew on the Neurolab mission, in which crewmembers were both exposed to angular and linear acceleration (see Figure 1.23) One objective of this experiment was to study the adaptation of the CNS by measuring the eye movements in response to angular and linear acceleration in space. Eye rotations can compensate for both the rotational and the translational components of head motion. On the Earth's surface, two major sources of linear acceleration are normally encountered. One is related to the Earth's gravity: the gravitational force pulls the body toward the center of the Earth, and the body opposes this force to maintain an upright standing posture. The other sources of linear acceleration arise in the side-to-side, up-down, or front-back translations of the head, which commonly occur during walking or running, and from the centrifugal force sensed when turning or going around corners. The body responds by tending to align the longitudinal body axis with the resultant linear acceleration vector. Put in simple terms, we have to exert an upward force such as to balance gravity when standing upright and to tilt into the direction of the turn when in motion. As mentioned above, in microgravity, the otoliths are not stimulated by head tilt, and therefore the eye movements in response to head pitch or roll are likely to be altered during and after spaceflight. The results of the centrifuge experiment have not confirmed this hypothesis, though: the torsional (along the line of sight) eye movement elicited by the linear acceleration (known as ocular counter-rotation) was unchanged in-flight and postflight relative to preflight. More investigations are therefore necessary to fully understand the adaptation of the compensatory eye movements during spaceflight.

New tests of the otolith function are currently introduced to evaluate the re-adaptation of eye movements in response to body tilt after spaceflight. Recently, we investigated the eye movements and the perception of crewmembers exposed to body rotation about an axis tilted from Earth's vertical (Figure 3.18, left). This off-vertical axis rotation (OVAR) causes, when rotation is in darkness at a constant low velocity, the perception of being successively tilted in all directions. Consequently, both a counter-rotation of the eyes and a perception of moving along the edge of an inverted cone, appear. At higher rotation rates the illusion is that of being upright, but moving along the edges of a cylinder (hence more translational motion), and eye movements are predominantly horizontal. Astronauts returning from space missions generally experience a larger

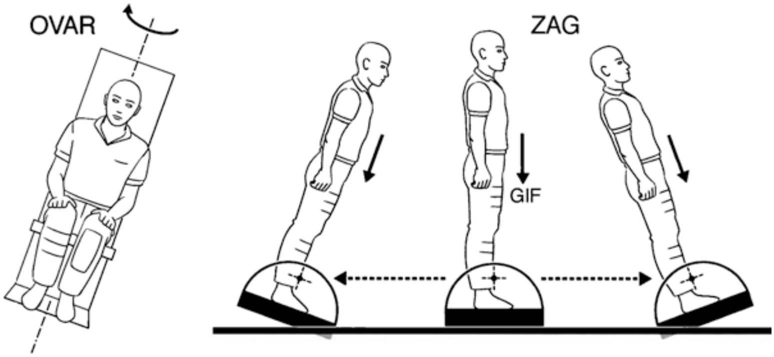


Figure 3.18. ***Left*. A Subject Rotating at Constant Velocity About an Axis Tilted Relative to the Vertical (Off-Vertical Axis Rotation) Has the Illusion of Describing Either a Conical or a Cylindrical Motion When Rotation Is at Low or High Velocity, Respectively. *Right*. In the z-Axis Aligned Gravitoinertial Force (ZAG) Paradigm, the Subject Is Sinusoidally Translated While Simultaneous Tilted Such as the Gravito-Inertial Force (GIF) Remains Aligned with the Longitudinal Body Axis.** Both OVAR and ZAG Allow the Investigation of the Ambiguity Between tilt and Translation Motion Perception During Stimulation of the Otoliths on Earth [Clément and Reschke, 2008]. (Credit Philippe Tauzin).

sense of translation during OVAR than preflight [Clément et al., 2007]. A follow-up experiment is currently being conducted to evaluate perceived tilt and translation in astronauts returning from spaceflight when they are exposed to ambiguous inertial motion cues. During this z-axis aligned gravito-inertial force (ZAG) paradigm, the astronauts sit in a chair that tilts within an enclosure that simultaneously translates so that the resultant linear acceleration vector remains aligned with the subject's longitudinal body axis (Figure 3.18, right). This condition provides a spaceflight analog in that tilt signals from the semi-circular canals conflict with the otolith signals that do not indicate tilt. The crewmembers generally perceive larger translational motion during this passive stimulation immediately postflight compared to preflight, which is in agreement with the OTTR hypothesis [Clément et al., 2008a].

Another experiment is being performed on crewmembers of the last shuttle missions, in preparation for the Mars landing. Subjects in complete darkness ride a motion-base simulator that moves in pitch, roll or translate, and they use a joystick to null-out these motion disturbances [Clément, 2011]. A tactile display countermeasure is being evaluated as an aid to piloting performance. The tactile display consists of a matrix of electromechanical tactile stimulators applied on the subjects' torso. These tactors convey orientation cues to the skin, such as the individual's amplitude of body tilt relative to gravity. Preliminary results indicate that such aid is a promising tool for reducing spatial disorientation mishaps by overcoming the limitations of multi-sensory integration when sensorimotor function is compromised [Rupert, 2000].

Another otolith test is achieved using a centrifuge where sitting subjects are displaced minimally from the rotation axis, so that one labyrinth becomes aligned on-axis, while the second labyrinth alone is exposed to the centripetal acceleration. This technique allows investigating subjective vertical and otolith-ocular responses during stimulation of the otolith on one side at a time.

It is interesting to note that the motion perception of astronauts when exposed to linear translation, centrifugation, or OVAR is fundamentally different postflight compared to preflight, whereas the eye movements, in particular torsion, are not. This dissociation between otolith-driven eye movement and perception during passive vestibular stimulation after spaceflight suggests that eye movements and orientation perception are governed by qualitatively different neural mechanisms. Ocular torsion is primarily a response of otolith activation by low-frequency linear acceleration along the interaural axis, whereas perception of tilt is primarily governed by the integration of graviceptive cues, including somesthetic, presumably centrally processed through neural models of the physical laws of motion. The peripheral vestibular organs would experience little or no changes after spaceflight (at least after short-duration flights), but the central processing of graviceptors inputs and the outputs of internal models for spatial orientation are likely to be affected. This dissociation would explain why otolith-driven eye movements appear relatively unaffected by microgravity, while perceptual and oculomotor responses depending on central vestibular processing can be greatly disrupted. Whether such dissociation is still present after longer stay in microgravity remains unknown.

Very recently, scientists have discovered that, on Earth, the eye movements also reflect an orientation to the resultant linear accelerations during turning. During either passive rotation, as in a centrifuge, or while walking or running around a curved path, the axis of eye rotation tends to align with the resultant axis of the summed linear accelerations. The same phenomenon occurs when viewing a visual scene that moves in the horizontal plane, but with the head tilted to the side. The eye movements (also called optokinetic nystagmus) are then oblique relative to the visual scene, as if they tried to align with the resultant of visual motion and gravity. Space experiments have shown that this gravity-oriented response was absent in microgravity, and that a return to the normal preflight response was observed 2 days after return to Earth.

Our eyes can rotate around three axes whereas normally only two are used in normal gravity. The plane where these axes are positioned is named "Listing's plane". This plane normally holds an upright position, but there are indications that its orientation changes in some conditions, such as in patients with vestibular disorders. A recent experiment performed onboard the ISS indicated that the orientation of the Listing's plane was consistently altered in some crewmembers in 0 g. Its elevation was tilted backwards by approximately 10°, and the azimuth angles of the left and right eyes also diverged in 0 g, with a statistically significant in the vergence angle and torsional eye position [Clarke, 2008]. It appears that given the lack of voluntary control of ocular torsion, the tonic otolith afferences are instrumental in the stabilization of torsional eye position and consequently of Listing's plane. The torsional divergence is the largest in those astronauts who also exhibit space motion sickness, which supports the otolith asymmetry hypothesis in generating space motion sickness (see Section 3.5.2).

On Earth, the eye movement responses tend to be asymmetric for upward and downward stimulation. For example, it is generally easier to follow a visual scene moving upward than downward. The interpretation generally proposed for this phenomenon was the following: when we walk, there is an apparent downward motion of the floor. However, this motion would be ignored, and the downward eye movements suppressed to pay more attention to a further distance in case obstacles could occur. Space experiments have shown that the vertical asymmetry tends to be eliminated in spaceflight, suggesting instead a role of gravity (presumably through a role of the otolith signals on the eye position) in this phenomenon [Clément, 1998].

3.4. Spatial orientation

3.4.1. Visual orientation

The visual system is addressed here principally in the context of its relationship to the vestibular system. Vision may compensate in large measure for modified otolith sensitivity. It helps in spatial orientation, and is essential to motor coordination. Astronauts working in microgravity must rely much more on vision to maintain their spatial orientation, as otolith signals no longer signal the direction of "down." It has long been known that moving visual scenes can produce compelling illusions of self-motion ("seeing is believing"). These visually induced illusions become even stronger in space, because visual cues are unhindered by constraints from the otoliths, which in microgravity do not confirm or deny body tilt. This has been confirmed in experiments wherein crewmembers observing a rotating visual field felt a larger sense of body rotation in space than on Earth [Lackner and DiZio, 2000]. It is interesting to note that frogs born in microgravity also showed stronger behavioral response to moving visual scenes when tested after their return to Earth than control animals born on Earth.

Crewmembers who remained seated in the relatively small *Soyuz*, Mercury, Gemini, and Apollo capsules rarely encountered orientation problems. However crews of the larger *Skylab* and shuttle reported occasional disorientation, particularly when they left their seats, and worked in unpracticed, visually unfamiliar orientations. The problem occurred both inside the spacecraft, and also outside, as when performing an EVA (Figure 3.19). For example, Bernard Harris, an astronaut of the *STS-63* shuttle mission reported: "As I was getting ready to step out of the spaceship, it felt like gravity was going to grab hold of me and pull me down toward Earth". Your natural response is to hesitate and grab on harder. I felt myself hanging on to the handrail and saying: "No, you're not going to fall toward the Earth, this is the same thing you've been seeing for the last 5 days."

Although episodes of visual disorientation are observed by many crewmembers, some seem more affected than others. In some individuals, static visual cues become increasingly dominant in establishing spatial orientation in microgravity. Other subjects are more "body oriented" and align their exocentric vertical along their longitudinal body axis. The latter individuals exhibit no problems in spatial orientation aloft even in the absence of visual cues for vertical orientation. Further, these individuals appear able to strengthen their perception of subjective verticality by using localized tactile cues, especially by pressure exerted on the soles of their feet.

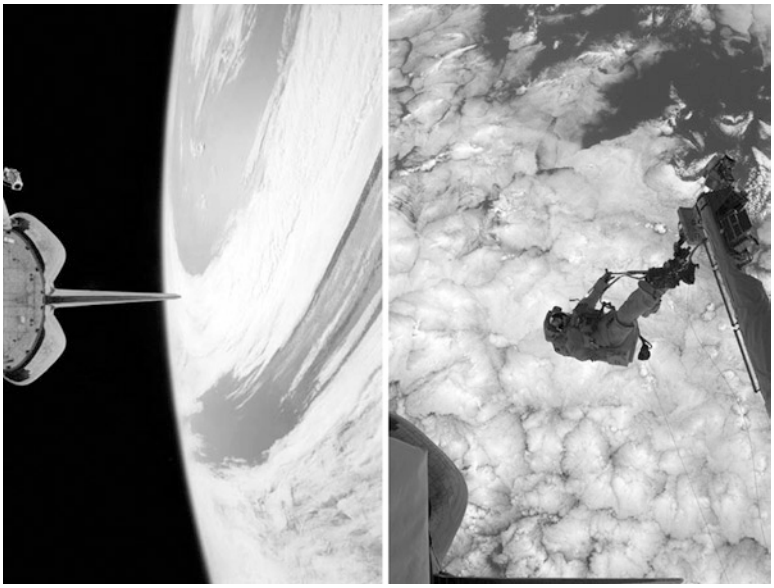


Figure 3.19. ***Left*: Because the Observation Windows of the Shuttle and ISS Face Earth, Astronauts Often Have the Sensation of Looking "Down" to Earth. *Right*: Astronauts During EVA Occasionally Feel Uncomfortable When Working Upside-Down or When Their Feet Point to the Earth "Below".** (Credit NASA).

Part of the difficulty of the people who predominantly rely on visual cues for spatial orientation is a result of the natural tendency to assume that the surface seen beneath our feet is the floor. When working "upside down" in the spacecraft, the walls, ceiling, and floors then frequently exchange subjective identities. Also, when viewing another crewmember floating upside down in the spacecraft, they often suddenly feel upside down themselves, because of the subconscious assumption carried over from life on Earth that people are normally upright. Fluid shift and the absence of otolith cues also contribute, and make some crewmembers feel continuously inverted, regardless of their actual orientation in the spacecraft. The inversion illusion may be understood using a model that includes an internal (idiotropic) orientation vector. This vector may also explain the sensation of the "downs" [Mittelstaedt and Glasauer, 1993].

There is also a natural tendency to perceive Earth as "down." Consequently, when looking at the Earth out of a window "above" their head, some crewmembers may feel that they are just standing on their head. Astronauts often report "if you lose something in weightlessness, you instinctively look down, which of course is not the solution" [Pettit, 2003].

It was once thought that these inversion illusions could trigger attacks of space motion sickness during the first several days in weightlessness. Many crewmembers have reported getting sick when looking out the space shuttle middeck window and find Earth at the top of the window frame instead of the bottom. However, though space sickness susceptibility eventually subsides, crewmembers on long-duration flights say that visual illusion episodes continue to occur. The observation that inversion illusions do not provoke space motion sickness as the flight progresses indicates a resolution of the factors that triggered the motion sickness early on. As a countermeasure for these visual illusions, it is thought that visual experience of working in unfamiliar orientations during preflight neutral buoyancy training (in a water tank) and virtual reality might help maintain spatial orientation while on orbit.

3.4.2. Cognition

The word "cognition" is often used in computer science-related fields to denote the level of activities that require "understanding" of what is going on, rather than merely signal-level reaction. We will review here the few cognitive functions that have been investigated during and after spaceflight.

Brain functions have developed on an evolutionary time scale to deal with the specific constraints that gravity imposes on human behavior. For instance, the world in which we live is primarily two-dimensional, particularly for Earth-bound creatures such as humans. While humans have constructed massive, three-dimensional (3D) structures such as skyscrapers, these edifices can essentially be described as multi-layered two-dimensional (2D) environments. Neural processes that allow us to navigate within this world may thus be specialized for the representation of 2D spatial maps. On Earth, we also expect to see objects disposed in particular fashions within the environment: objects lying on a table will usually be found in a stable upright or horizontal position; objects in free fall accelerate downward; we usually meet people in an upright position. In building these expectations, we are essentially modeling the expected behavior of objects in the world. These models can be used to predict upcoming events and optimize performance on a variety of cognitive tasks [McIntyre et al., 2001].

3.4.2.1. Navigation

Vertebrate brains form and maintain multiple neural maps of the spatial environment that provide distinctive, topographical representations of different sensory and motor systems. For example, visual space is mapped onto the retina in a 2D coordinate plan. This plan is then remapped to several locations in the central nervous system. Likewise, there is a map relating the localization of sounds in space and one that corresponds to oculomotor activity. An analogous multi-sensory space map has been demonstrated in the mammalian hippocampus, which has the important function of providing short-term memory for an animal's location in a specific spatial venue. This neural map is particularly focused on body position and makes use of proprioceptive as well as visual cues. It is used to resume the location at a previous site; a process called navigation.

This system of maps must have appropriate information regarding the location of the head in the gravitational field. So it follows that the vestibular system must play a key role in the organization of these maps. Only recently has this been demonstrated by experiments carried out in space. During an experiment performed on board Neurolab, rats ran a track called the Escher staircase, which guided the rats along a path such that they returned to their starting location after having made only three 90° right turns. On Earth, rats could not run this track. But in space, it provided a unique way to study the "place cells" in the hippocampus that encode a cognitive map of the environment. The rats had multi-electrode recording arrays chronically implanted next to their hippocampal place cells. Recordings in space indicated that the rats did not recognize that they were back where they started, after only three 90° right turns.

Such studies could help to explain the visual inversion illusions and the navigation difficulties experienced by some astronauts when they arrive in space. A weightless environment presents a true 3D setting where Newton's laws of motion prevail over Earth-based intuition. We normally think in terms of two dimensions when we move from place to place. However, in orbit, one might decide the best way is to go across the ceiling and then sit on a wall.

In addition, each module of the ISS provides a local visual frame of reference for those working inside. Inside the ISS, the modules are connected at 90° angles, so not all the local frames of reference are co-aligned. It is sometimes difficult to remain oriented, particularly when changing modules. Even after living aboard for several months, it is difficult to visualize the three-dimensional spatial relationships among the modules, and move though the modules instinctively without using memorized landmarks. Crewmembers not only need to learn routes, but also develop 3D "survey" knowledge of the station. Disorientation and navigation difficulties could be an operational concern in case an emergency evacuation is required in the event of a sudden depressurization or fire. Researchers are working on you-are-here maps that would be displayed in strategic locations on the ISS, so that visitors, first time or experienced astronauts, will be able to quickly identify escape route or emergency equipment.

3.4.2.2. Mental rotation

On Earth, gravity provides a convenient "down" cue. Large body rotations normally occur only in a horizontal plane. In space, the gravitational down cue is absent. When astronauts roll or pitch upside down, they must recognize where things are around them by a process of mental rotation that involves three dimensions, not just one.

It is well known that on Earth, a familiar visual environment, a face or a printed text cannot be recognized or analyzed when it is tilted by more than roughly 60°. In a very simple experiment, I once asked one crewmember to report the tilt angle of his body with respect to the inside of the spacecraft from which he had more difficulty in mentally rotating the visual features. The reported angle was about 60° on the first day in-flight, 90° on the second day, but after 3 days in-flight his perception was independent of the respective orientations. One interpretation is that weightlessness, by providing a release of the gravity-dependent constraint on mental rotation, would facilitate the processing of visual images in any orientation with respect to the body axis.

In a series of subsequent mission, a mental rotation paradigm with pictures of 3D objects was tested on several cosmonauts (Figure 3.20). Responses showed that the average rotation time per degree was shorter in-flight than on the ground. This difference seems to be particularly marked for stimuli calling for mental rotation about a roll or a pitch axis. An actual body rotation around both of these axes would induce different responses from the otolith organs in weightlessness compared to Earth. However, a later study in which the repertoire of objects was different among all experimental sessions to avoid a learning effect, showed no significant differences in rotation time in space versus ground data [Léone, 1998]. So, the results are inconclusive at this point and further studies are needed to investigate whether mental rotation is facilitated or not in microgravity. One concern is that a poorer ability to mentally rotate the visual environment could be a determinant factor for the apparition of space motion sickness. Another concern is the ability for the astronauts to recognize their fellow crewmembers when upside-down. However, preliminary tests suggest that after a few days in space it is less difficult to identify an upside-down face (the so-called "inversion effect") in space than on Earth.[8]

Other experiments have investigated whether it was easier to detect the presence of a symmetry axis in absence of gravity. For example, it is well known that on Earth, the

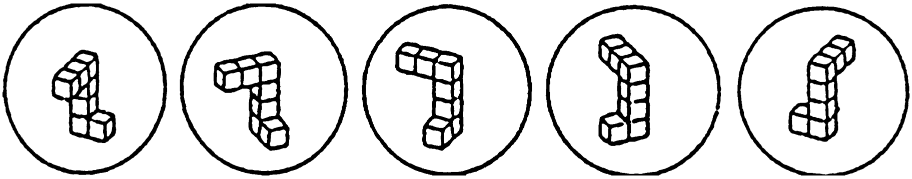


Figure 3.20. Examples of Shapes Used for a Mental Rotation Test. When the Shape on the Extreme Left Is Presented with, Let's Say, the Shape on the Extreme Right (a 180° Rotation), the Time Taken to Decide that Both Shapes Are the Same Is About 5 s. When the Shape on the Extreme Left Is Presented with the Shape in the Middle (a 90° Rotation), the Response Time Is Now Only 2.5 s. Therefore the Speed of Mental Rotation in This Test Is About 33°/s.

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[8] There was one instance on a shuttle mission where a crewmember was "lost". Several of his crewmates looked for this individual but couldn't find him…yet all the while he was right in front of them. The lost crewmember was actually inverted relative to those looking for him [Millard Reschke, 2006].

vertical axis of symmetry is easier to identify than a horizontal or an oblique axis of symmetry. A change in the position of the head relative to the trunk on Earth influences symmetry detection. One experiment performed in space on five astronauts indicated that both vertical and horizontal axes of symmetry were equally easy to identify [Léone, 1998].

Interestingly enough, mental tasks that demand logical reasoning, decision-making, as well as memory retrieval functions, seem unimpaired during spaceflight. This result is in conflict with what is frequently reported by crewmembers. That is, it is difficult to evaluate elapsed time periods while in space.

3.4.2.3. Mental representation

An accurate representation of the visual environment is crucial for the successful interaction with objects in an environment. It is clear that humans have mental representations of their spatial environment and that these representations are useful, if not essential, in a wide variety of cognitive tasks such as identification of objects and landmarks, guiding actions and navigation, and in directing spatial awareness and attention.

In physics, a coordinate system that can be used to define position, orientation, and motion is called a reference frame. It has been argued that the Earth's gravitational field is one of the most fundamental constraints for the choice of reference frames for the development and the use of cognitive representations of space. For example, a subject looking at a diamond-shaped figure (in retinal coordinates) perceives a square-shaped figure when he/she and the figure are both tilted relative to gravity. This result indicates that the perception of the form of an object generally depends more on the orientation of the object in world (spatial) coordinates than on its orientation in retinal coordinates. In other words, gravity is critical for the extraction of an object's reference frame.

One problem with ground-based studies on perception is that tilting the observer relative to gravity on Earth creates a conflict between perceived gravitational (extrinsic) vertical and retinal- or body-defined (intrinsic) vertical, but does not suppress the gravitational information. On the other hand, the loss of the gravitational reference in spaceflight provides a unique opportunity to differentiate the contribution of intrinsic and extrinsic factors to the spatial orientation system.

Measuring the changes in the mental representation of an object throughout a space mission is a simple way to assess how the gravitational reference frame is taken into account for spatial orientation. Results of space studies by our group suggest that the absence of the gravitational reference system, which determines on Earth the vertical direction, influences the mental representation of the vertical dimension of objects and volumes. For example, I once asked a French astronaut to write his name with his eyes closed vertically and then horizontally on a notebook attached by Velcro to his knee. The physical length dimension of these words on the page was compared between in-flight and preflight tests. Results showed that the length of the written words decreased in-flight for both vertical and horizontal directions, but the vertical direction was the most affected [Clément et al., 1987]. In another astronaut, the reduction in the vertical length of words was observed during several days after returning from a 28-day space mission (Figure 3.21). It is interesting to note that in both experiments,

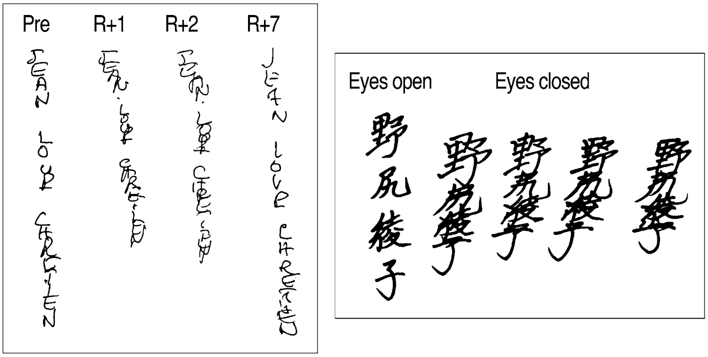

Figure 3.21. ***Left*: Vertical Writing Test with the Eyes Closed in an Astronaut Before (Pre) and After (R+1 to R+7 Days) a Spaceflight. *Right*: Vertical Wri-ting Test in a Vestibular Patient.** (Adapted from Fukuda [1983]).

the size of the letters did not change in-flight or postflight, but the vertical distance between them was decreased. This observation indicates that the changes were not due to an alteration in proprioception or motor control. Interestingly, these tests are variants of tests traditionally used in oriental medicine (the Fukuda Writing test, the Square Drawing test) to diagnose patients with impairment in motor function (when the size of all characters is irregular) from those with vestibular disorders (the writing or drawing is deviated to one side). And the astronauts' responses are close to those of patients with otolithic disorders on Earth. These results suggest that adaptive changes in the mental representation of a vertical layout of letters take place when the gravitational frame of reference is removed either by microgravity or by central disorders [Clément and Reschke, 2008].

During another test, two crewmembers were requested to draw the well-known Necker's cube. This figure is the simplest representation of a three-dimensional object in a two-axis coordinate system. Comparison between the length of the lines between the cubes drawn on the ground and the cubes drawn in space revealed a 9% decrease in length in the vertical dimension (i.e., the height) of the cubes drawn in weightlessness (Figure 3.22). Similar results have been found in another study involving two astronauts. The trajectory of hand-drawn ellipses in the frontal plane in the air with their eyes closed revealed a 10–13% decrease in the vertical length of the ellipses, whereas the horizontal length of the ellipses was basically unchanged. This result supports our hypothesis that the mental representation of the vertical dimension of objects or volumes is altered during exposure to weightlessness.

3.4.2.4. Depth perception

Depth perception is based on accommodation, binocular disparity, motion parallax, as well as aerial and geometrical perspectives (Figure 3.23, left). In the absence of atmosphere and with different lighting conditions affecting color and contrast, as in spaceflight, aerial perspective is presumably the most reliable of cues for depth perception. Space experiments have begun to investigate the role of depth cues in absence of a gravitational frame of reference. Howard et al. [1990] had shown that the perception of concavity or convexity of a shape depends on a "light comes from above" assumption,

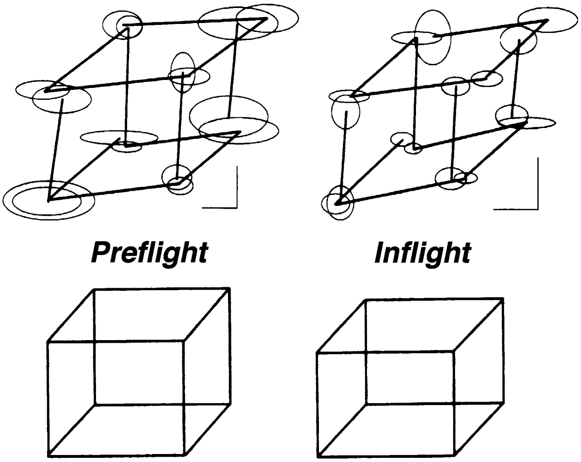

Figure 3.22. ***Top*: Mean ± SD of Each Point of Cubes Drawn by an Astronaut Preflight and In-Flight. *Bottom*: Averaged Mean Preflight and In-Flight Cubes. Horizontal and Oblique Lines Were Unchanged, but the Vertical Lines Were Shorter in Microgravity.** (Adapted from Lathan et al. [2000]).

Figure 3.23. **Monocular Cues for Depth Include Aerial Perspective, Which Entails the Loss of Contrast, Color, and Shading with Increasing Distance Due to Scattering of Light in the Atmosphere (*left*) and Geometrical Perspective, in Which Objects Appear Smaller When They Are Farther Away (*right*).** Aerial and Geometrical Perspectives Are Both Affected by the Spaceflight Environment, Either Directly or Indirectly.

where "above" depends on the head orientation relative to the object and gravity. During the Neurolab mission, crewmembers were presented with convex or concave shaded figures. After several days in space, they could not use so reliably that light information for depth, because they had been exposed to situations where the light source could come from any direction while they were free-floating in the cabin [Oman, 2003].

Our ISS experiment called 3D-SPACE (see Figure 3.10) is using classic geometrical illusions of size, which on Earth generate inaccurate judgments because they provide misleading depth cues. Those illusions based on perspective depth cues are particularly relevant to the space environment. Indeed, geometrical perspective uses converging lines and vanishing points to determine how much an object's apparent size changes with distance (Figure 3.23, right). It is based on the principle that there is a theoretical horizon line representing the point of view of the observer, and that the angle of converging lines toward a vanishing point, generally in the straight-ahead direction, provides depth information. In the absence of a gravitational reference, such as in microgravity, it is more difficult to define a horizontal line. Also, previous studies have shown significant deviations in the vertical position of the eye in microgravity due to the stimulation of the otolith organs by changes in the amplitude of the gravito-inertial forces, which could alter the direction of the "straight ahead." Consequently, because the rules of geometrical perspective are less accurately defined in microgravity, the subjects should rely less on the perspective cues for depth perception. The preliminary data from this experiment tend to support this hypothesis.

The results of these studies may have important consequences for human performance during spaceflight. For example, if an astronaut cannot accurately visualize the volume of the station, its surroundings, or a planetary surface, navigation may cause delays and frustration. There may also be consequences for space habitat design if squared volumes do not look square to people in space. Virtual reality training might be a way to train the astronauts to compensate for such altered spatial representation.

Recent research studies have used electroencephalogram (EEG) recordings to monitor and measure working memory and other indicators of cognitive ability. A recent experiment conducted over the course of three spaceflights quantified the EEG oscillations at 10 Hz, which are the most prominent rhythms observed in subjects who are awake with their eyes closed. This activity increased in five cosmonauts in-flight compared to preflight. The authors of this study attribute this increase to a reduction in graviceptive inputs to cortical networks participating in the mental representation of space [Chéron et al., 2006]. Further investigations carried out in space will perhaps reveal that other higher cortical functions are impaired in weightless conditions. The combination of virtual reality with EEG recordings (for the measurement of evoked-related potentials and brain mapping) should soon provide insightful results on the adaptive mechanisms of cerebral functions in absence of gravity.

How will the cognitive processes of spatial orientation differ from the terrestrial norm after a long absence of a gravitational reference? We speculate that the way of processing three dimensions will be more developed. Creativity will certainly be more three-dimensional and definitely thinking will be out of the gravitational box. Like the way culture and language influences our ability to think creatively, being free from gravity will elicit thoughts never before possible for the human mind, and thus give opportunities for new art and scientific discoveries [Pettit, 2003].

3.5. What do we know?

3.5.1. Space motion sickness experience

The severity of SMS is categorized depending on its impact upon crew performance (Table 3.1). For example, "Mild" SMS has no operational impact, because the crewmember can still perform all the required activities. "Moderate" or "Severe" SMS are

Table 3.1. NASA Categorization of Space Motion Sickness According to the Severity of Symptoms.

None	No signs or symptoms reported
Mild	One to several transient symptoms No operational impact All symptoms resolved in 36–48 h.
Moderate	Several symptoms of a persistent nature Minimal operational impact All symptoms resolved in 72 h.
Severe	Several symptoms of a persistent nature Significant performance decrement Symptoms may persist beyond 72 h

operational concerns since the workload must be redistributed among the remaining, unaffected crew.[9]

In the space shuttle missions between 1981 and 2000, about 69% of the 471 crewmembers making their first flight reported symptoms of SMS. About 35% reported mild symptoms, 23% moderate symptoms, and 11% severe symptoms. Most recovered by the end of the third day in space. In a few cases in the Russian and U.S. missions, however, crewmembers were ill for 7–14 days.

The severity of SMS among those making a second flight remained unchanged in 56% of crewmembers, whereas a slight improvement was observed in 35%, but even more symptoms were noted in 9%. This indicates that symptoms are not significantly reduced on a following flight.

In addition to feelings of vertigo and nausea, SMS can cause sopite syndrome, which includes lack of motivation to work or interact with others, drowsiness, fatigue, and the inability to concentrate. Sopite syndrome is often a byproduct of dizziness experienced by astronauts during space travel.

SMS is self-limited. Complete recovery from major symptoms (i.e., adaptation to the spaceflight environment) occurs within 2–4 days. After complete adaptation occurs, crewmembers appear to be immune to the development of further symptoms. This development of immunity to further SMS symptoms was demonstrated by rotating chair tests, designed to provoke an SMS response, that were conducted in-flight during *Skylab* missions.

3.5.2. Theories for space motion sickness

Two major theories advanced to account for SMS are the fluid shift theory and the sensory conflict, also known as the neural mismatch, sensory mismatch, or sensory rearrangement theory [Crampton, 1990]. Although both theoretical positions have some merit and neither is ideal, the fluid shift theory does not explain the development

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[9] In the jargon of the flight surgeons, “Mild” symptoms are sometimes referred to “one bag”, “Moderate” to “two bags”, and “Severe” to “three bags”.

of motion sickness during spaceflight (we don't get sick when lying in a bed). While the fluid shift theory of SMS could be associated with sensory conflict, there are mechanisms whereby the headward fluid shift accompanying microgravity could bypass the classic vestibular inputs to induce vomiting.

Briefly, the sensory conflict theory of motion sickness assumes that human orientation in 3D space, under normal gravitational conditions, is based on at least four sensory inputs to the central nervous system. The otolith organs provide information about linear accelerations and tilt relative to the gravity vector; angular acceleration information is provided by the semicircular canals; the visual system provides information concerning body orientation with respect to the visual scene or surround; and touch, pressure, and somato-sensory (or kinesthetic) systems supply information about limb and body position. In normal environments, information from these systems is compatible and complementary, and matches that expected on the basis of previous experience. When the environment is altered in such a way that information from the sensory systems is not compatible and does not match previously stored neural patterns, motion sickness may result.

The sensory conflict theory postulates that motion sickness occurs when patterns of sensory inputs to the brain are markedly re-arranged, at variance with each other, or differ substantially from expectations of the stimulus relationships in a given environment. In microgravity, sensory conflict can occur in several ways. First, there can be conflicting information (i.e., regarding tilt) transmitted by the otoliths and the semicircular canals. Sensory conflict may also exist between the visual and vestibular systems during motion in space; the eyes transmit information to the brain indicating body movement, but no corroborating impulses are received from the otoliths (such as during car sickness). A third type of conflict may exist in space because of differences in perceptual habits and expectations. On Earth, we develop a neural store of information regarding the appearance of the environment and certain expectations about functional relationships (e.g., the concepts of "up" and "down"). In space, these perceptual expectations are at variance, especially during the inversion illusions described above.

It is important to note that no single course of sensory conflict appears to entirely account for the symptoms of space sickness. Rather, it is the combination of these conflicts that somehow produces sickness, although the exact physiological mechanisms remain unknown. Thus, sensory conflict explains everything in general, but little in the specific. Shortcomings of the sensory conflict theory include: (a) its lack of predictive power; (b) the inability to explain those situations where there is conflict but no sickness; (c) the inability to explain specific mechanisms by which conflict actually gives rise to vomiting[10]; and (d) the failure to address the observation that without conflict, there can be no adaptation. The hypotheses outlined below may be helpful in overcoming some of the weaknesses associated with the construct of this theory.

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[10] It has been proposed that motion sickness results from the activation of a vestibular mechanism whose physiological function is the removal of poisons from the stomach. Nausea and vomiting would also tend to keep a disoriented or dizzy individual from moving about the environment in search of food when he would be at risk doing so [Money, 1990].

Some investigators have proposed a mechanism complementary to the sensory conflict theory to explain individual differences in SMS susceptibility. They suggest that some individuals possess slight functional imbalances, for example weight differences, between the right and left otolith receptors that are compensated by the CNS in 1 g. A weight imbalance between the left and right otoconia is reasonable since there is a continual turnover of otoconia, and it is unlikely that the two otoliths would ever weigh exactly the same. This compensation is inappropriate in 0 g, however, because the weight differential is nullified and the compensatory response (either central or peripheral) is no longer correct for the new inertial environment. The result would be a temporary asymmetry producing rotary vertigo, inappropriate eye movements, and postural changes until the imbalance is compensated or adjusted to the new situation. A similar imbalance would be produced upon return to 1 g, resulting in postflight vestibular disturbances. Individuals with a greater degree of asymmetry in otolith morphology would thus be more susceptible to SMS.

A sensory compensation hypothesis has also been proposed. Sensory compensation occurs when the input from one sensory system is attenuated and signals from others are augmented. In the absence of an appropriate graviceptor signal (or perhaps the presence of atypical signals) in microgravity, information from other spatial orientation receptors such as the eyes, the semicircular canals, and the neck position receptors would be used to maintain spatial orientation and movement control. The increase in reliance on visual cues for spatial orientation could be explained by this mechanism. Closely related to this sensory compensation hypothesis is the OTTR hypothesis already discussed (see Figure 3.7).

3.5.3. Countermeasures

The disruptive nature of SMS, occurring as it does during the early, critical stages of a mission, has led to a variety of approaches for the prevention or control of this medical problem.

Prediction of susceptibility has been a major objective of the SMS research. Various approaches ranging from the use of questionnaires, history, experience or personality traits, vestibular function tests, physiological correlates, and tests in specific nauseogenic environments have been directed toward the question of SMS susceptibility. However, striking differences were found in the pattern of symptoms generated during flight compared to the pattern generated during the ground-based tests. Further, the specific nature and time course of in-flight symptomatology were highly variable. The preflight questionnaire results did not correlate with the reported incidence of SMS. Differences in the results between susceptible and non-susceptible crewmembers for each of the preflight tests were not significant, nor was the correlation between susceptibility to motion sickness in the ground-based tests and susceptibility to SMS. Individual variations in preflight experience, medications, in-flight tasks (i.e., mobility), and personal strategies for symptom management have further compounded the problem. Consequently, the use of a single ground-based parameter or test procedure is inadequate for predicting SMS susceptibility. Despite the inability to identify ground-based predictors of SMS susceptibility, one reasonably accurate predictor was identified, and that is spaceflight itself. Of 16 crewmembers who had flown two or more space missions, the response pattern of only three changed from one flight to the next.

While research on predictors of SMS has been inconclusive, some progress has been made in the development of countermeasures. Current areas of investigation include preventive training techniques, in-flight techniques for minimizing head and body movement, and use of anti-motion sickness drugs [Lackner and DiZio, 2006].

Attempts by the Russian program to prevent SMS by pre-selection of individuals with a high tolerance to motion sickness during complex vestibular stimulation have not met with success. Vestibular testing was once used in the U.S. space program for the early selection of astronauts, but it is no longer used for shuttle and ISS crewmembers. Vestibular training prior to spaceflight in the Russian space program has primarily involved Coriolis and cross-coupled angular accelerations. However, this training is rather demanding for the crewmembers and its efficacy against SMS has never been proven.

One preventive technique, developed at the NASA Ames Research Center, is a combined application of biofeedback and autogenic therapy (a learned self-regulation technique). This technique proved quite successful in controlling some symptoms of SMS associated with the autonomic nervous system, such as nausea and vomiting. In some individuals, autogenic feedback has produced improvement in motion tolerance with as little as 6 h of training. However, it does not work with all individuals.

Training procedures that pre-adapt astronauts to the sensory stimulus rearrangements of microgravity gave promising results. The NASA Preflight Adaptation Trainer (PAT) provides astronauts with demonstrations of and experience with altered sensory stimulus rearrangements that produce perceptual illusions of various combinations of linear and angular self- or surround-motion (Figure 3.24). Crewmembers who were exposed to this training before flight had a significant reduction (19–54% depending on the symptoms) in the severity of SMS symptoms by comparison with those who were not exposed to it.

Because crewmembers have reported that rapid head movements worsen the nausea and spatial disorientation associated with SMS, head and neck restraints that restrict such movements have been used, but with limited success.

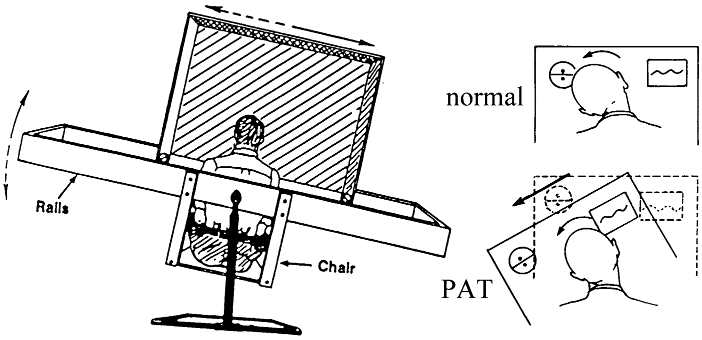

Figure 3.24. Preflight Adaptation Training. Before the Flight, Crewmembers Are Passively Tilted in Roll or in Pitch While Exposed to a Lateral Translation of the Visual Scene (Such as on the *left panel*) or to a Fore/Backward Translation, Respectively, in Order to Induce a Reinterpretation of Their Otolith Signals by the Visual System. (Credit NASA).

Drugs that diminish the SMS symptoms are being used and studied. During the Apollo, *Skylab*, and the first shuttle missions, scopolamine and a combination of scopolamine and dextroamphetamine, given orally, were used to treat SMS, with limited success. Since STS-36 (1990), shuttle and ISS crewmembers experiencing severe SMS have been treated primarily via intramuscular injection (25 or 50 mg) or suppository (25 mg) of promethazine. Oral promethazine or a combination of promethazine and dexedrine are also used. While promethazine is effective as therapy, clearly there remains room for improvement: 25% of crew treated become sick the next day, the injections are painful, and are usually only administered prior to sleep due to sedating effects. Mild cases of SMS – involving "sopite" symptoms such as drowsiness, lethargy, and short-term memory deficits – typically go untreated. Recent research indicates, however, that promethazine can cause deleterious side effects that further degrade human performance, including reaction time, grammatical reasoning ability, and pattern recognition, and negatively impact mood and sleep. No SMS drug, including promethazine, has yet been identified that is clinically acceptable for prophylactic use during an EVA or by pilots during landing. Promethazine cannot be used with the anti-orthostatic drug midodrine on landing day. The lack of effective SMS prophylactic drugs has a dramatic impact on crewmember efficiency: timeline developers deliberately reduce scheduled activities by 25% during the first 2 days, hoping crewmembers will limit their head movements [Oman, 1998].

Russian crews employ different drug formulations and procedures to prevent and treat SMS, and report a somewhat lower overall incidence. Progress has been made since 1990 on the physiology of nausea and vomiting, receptor targeted anti-emetics, as well as phenotypic and genotypic biomarkers of motion sickness susceptibility. New intranasal formulations of traditional drugs are in development. Unfortunately SMS has received relatively little clinical research attention recently. The level of SMS risk control actually being achieved and the effects of SMS drug use on sensorimotor adaptation remain poorly understood. Vomiting in 0 g is not dangerous, except during EVA. NASA currently manages the risk by prohibiting EVAs during the first three mission days. Nonetheless, there has been at least one episode. On planetary missions, a limited number of suits are planned for all mission phases. A vomiting episode renders a suit non-reusable, due to biological contamination. In the absence of a proven effective SMS prophylactic drug, suit containment is essential, and should be designed into the new suit from the start. Physiological issues are involved in design and test, and should not be entirely relegated to engineers [Oman, 2007].

Although past research has yielded a great deal of information applicable to SMS, a definitive solution to this vexing problem is urgent. Among the objectives of current SMS research is the development of: (a) more precise predictive indices; (b) more effective drug treatments; (c) more efficient preflight adaptation procedures; (d) methods to evaluate performance impairment induced by SMS and anti-motion sickness drugs; and (e) the early detection of incipient symptoms.

Over the past 50 years, efforts in space neuroscience have been directed at understanding the acute changes that occur in the neurovestibular and sensorimotor systems, mostly during short-duration space missions. Very few experiments have been performed during the first minutes or hours of adaptation to microgravity and re-adaptation to Earth's gravity. This is a shortcoming of all the research that has been performed during the space shuttle program. Major research emphasis should be placed on obtaining an understanding of the acute changes that occur during the first few minutes and hours of spaceflight, and immediately after landing. These periods are characterized by transitions in gravitational levels, which have an impact on sensorimotor functions. The suborbital flights might be an opportunity to investigate these acute changes. The results of this research will be useful for exploration missions that will include several transitions between gravitational levels, and for commercial suborbital missions as well.

Based on our previous experience in orbital and parabolic flight, space motion sickness, mal de débarquement, sensorimotor disruptions in eye movements, postural stability, and motor coordination are likely to occur in the participants of commercial suborbital missions McDonald et al. [2007]. Some strategies have been proposed to overcome these problems, such as sensorimotor adaptation during periods of reduced and enhanced gravity on board parabolic flight and centrifuges [Karmali and Shelhamer, 2010]. Further research into the required quantity and timing of these pre-adaptation flights and the tasks conducted during these flights are required to improve safety and comfort of the participants during suborbital flights.

Before a mission to Mars can safely be undertaken, the adaptive processes of the sensory, motor, and cognitive systems to microgravity need to be better understood, and countermeasures must be devised for a faster re-adaptation of the CNS functions that are expected to occur following the transitions between various gravitational environments. In particular, future investigations should address the following issues:

(a) Motion sickness upon return to a gravitational environment, including postflight motion sickness, needs to be better understood and mitigation strategies developed.
(b) The dynamic range of the adaptation of sensorimotor responses in various gravitational environments needs to be identified. This may be accomplished by using a centrifuge on board the ISS or in a Moon habitat. Accurate predictions of the effects Mars gravity may be accomplished via modeling.
(c) It is not known if permanent functional deficits result from the decrease in afferent input to the vestibular, proprioceptive and somatosensory systems as a function of the adaptation associated with long exposure to 0 or 0.38 g.
(d) Morphological or structural changes in CNS and neuromuscular functions that may account for these deficits need to be identified (Figure 3.25).

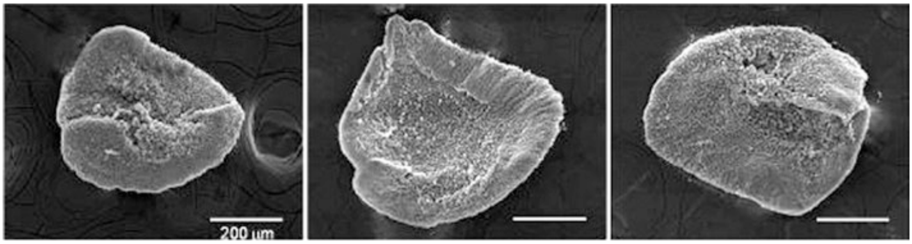

Figure 3.25. Scanning Electron Micrographs of Otoliths from Quail Embryos That Were Raised from Fertilization in Microgravity (*left*), in an Onboard 1-g Centrifuge (*center*), and in a 2-g Centrifuge on Earth. (Adapted from Evans et al. [2009]).

(e) The procedures that produce rapid and complete adaptation to Martian gravity and Earth's gravity after exposure to microgravity must be validated. This may be accomplished using Martian gravity simulation by executing parabolic flight maneuvers on Earth, or using a centrifuge on board the ISS or in a Mars habitat.

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