Chapter 4

PHYSIOLOGICAL TARGETS OF ARTIFICIAL GRAVITY: THE SENSORY-MOTOR SYSTEM

Eric Groen,[1] Andrew Clarke,[2] Willem Bles,[1] Floris Wuyts,[3] William Paloski,[4] and Gilles Clément[5,6]

[1] *TNO, Soesterberg, The Netherlands*
[2] *Charité Medical School, Berlin, Germany*
[3] *Antwerp University, Antwerp, Belgium*
[4] *NASA Johnson Space Center, Houston, Texas, USA*
[5] *Centre National de la Recherche Scientifique, Toulouse, France*
[6] *Ohio University, Athens, Ohio, USA*

This chapter describes the pros and cons of artificial gravity applications in relation to human sensory-motor functioning in space. Spaceflight creates a challenge for sensory-motor functions that depend on gravity, which include postural balance, locomotion, eye-hand coordination, and spatial orientation. The sensory systems, and in particular the vestibular system, must adapt to weightlessness on entering orbit, and again to normal gravity upon return to Earth. During this period of adaptation, which persists beyond the actual gravity-level transition itself the sensory-motor systems are disturbed. Although artificial gravity may prove to be beneficial for the musculoskeletal and cardiovascular systems, it may well have negative side effects for the neurovestibular system, such as spatial disorientation, malcoordination, and nausea.

Figure 4-01. Astronauts during extravehicular activities have experienced "fear of height" (acrophobia) in which vision and vestibular cues clearly play a major role. Photo courtesy of NASA.

1 STRUCTURE AND FUNCTION OF THE SENSORY-MOTOR SYSTEM

The human *sensory-motor system* allows us to ascertain the status of our body, sense our environment, make relevant adjustments in relation to this environment, or move around in our environment to achieve various goals. The *sensory* part, relying on our body's numerous physiological sensors, detects the motion or position of body parts relative to each other (spatial awareness) or to the environment (spatial orientation). The *motor* part refers to our movement within and relative to our environment. Sensing and moving around in the environment cannot be regarded as separate entities: any movement will stimulate the sensors, and immediately alter their afferent information to the *central nervous system* (CNS). For example, a rapid head movement is sensed by the vestibular organs, which in turn signal to the extraocular muscles to generate a compensatory eye movement. If this were not the case, blurred vision would occur. In addition to eye-head coordination, the vestibular system is involved in various other human sensory-motor functions, including maintenance of posture, gait stabilization, general coordination of limb movement, and spatial orientation.

As is the case for all species we have evolved a sensory apparatus that is optimally matched to our natural behavioral repertoire under terrestrial gravity conditions. Thus we achieve upright bipedal posture, maintain attention to the world around us, and move within our habitat.

The afferent signals from the vestibular organs converge in the *central vestibular system* situated in the brainstem, and are integrated with visual inputs from the peripheral retina, proprioceptive and tactile inputs from skin, muscles and joints. This convergence allows sensory integration that is essential for maintaining balance and spatial orientation. Resultant motor outputs primarily contribute to the regulation of our eye movements to ensure gaze stabilization and to the anti-gravity muscle apparatus that keep us upright. Signals from the vestibular system are also transmitted to the cerebellum and to higher centers in the thalamus, hippocampus, and cortex, which are involved in subjective perception of motion and spatial orientation. This perception involves synthesis and assignment of some meaning to sensory input, taking into account our expectations in the behavioral context and our prior experience and culture. These areas are also involved in related processes, including learning, adaptation, and habituation.

The vestibular organs in the inner ear comprise the *semicircular canals*, which transduce rotation, and the *otolith organs*, which transduce linear translation of the head and head tilt relative to gravity (Figure 4-02). To maintain clear vision during head movement, the afferent signals from the semicircular canals drive the extraocular muscles via a three-neuron arc, the so-called *vestibulo-ocular reflex (VOR*), to facilitate compensatory eye movements, With a transmission time of approximately 10 ms, this represents perhaps the fastest reflex in the human body.

Figure 4-02. The labyrinth or vestibular apparatus is the organ of balance. Located in the inner ear, it consists of three semi-circular canals and the otolith organs (utricle and saccule).

In contrast to the semicircular canals, which respond to angular acceleration of the head, the otolith organs sense linear accelerations of the head. Each of the otolith organs, the utricle and the saccule, possesses a sensory epithelium populated by several thousand hair cells whose sensory hairs, or *cilia*, project into a gelatinous membrane. Embedded in this membrane are a multitude of densely packed, small crystals of calcium carbonate, the *otoconia* (Figure 4-22). The otoconial mass (with a specific density 2.7 fold greater than the surrounding endolymph) functions as an inertial mass, which is displaced proportionally to the linear acceleration of the head during any movement. In turn, the sensory hairs (cilia) of the hair cells are sheared by the movement of the otoconial membrane. It follows that during any constant velocity translation the otolith afferences do not signal movement. The otolith afferences, however, continuously monitor the gravito-inertial force generated by head tilt relative to gravity.

Each hair cell possesses a preferred polarization direction in which it responds maximally. The cell population is distributed across the maculae of the utricle and saccule, so as to encompass head accelerations in any direction. While the utricles are orientated approximately in the horizontal plane, and the saccules in the vertical planes of the head, i.e., each covering the corresponding two dimensions of movement, the macular form is by no means planar, a feature which introduces redundancy and ensures omnidirectional sensing of linear acceleration.

A major role of the otolith organs is to provide information about head orientation to gravity. If the head and body begin to tilt, the vestibular nuclei in the brainstem will automatically relay the information from the otolith organs via the vestibulo-spinal pathways to activate the muscles necessary to correct our posture. In such a situation, the interpretation of otolith signals involves the problem of distinguishing between *tilt* relative to gravity, which is equivalent to a constant linear acceleration, and linear acceleration due to *translation*. The general explanation is that, over the course of ontogenesis, the CNS learns to understand that gravity is constant in direction and magnitude, whereas linear accelerations caused by locomotion are usually variable. With this knowledge, the CNS is able to separate out gravity as the low-frequency component. The remaining high-frequency component of the sensed accelerations can subsequently be ascribed to self-motion. Although this scheme has been successfully described by various mathematical models (Merfeld *et al.* 1993, Bos and Bles 2002), the neural mechanisms underlying this separation are not yet fully understood.

Figure 4-03. Otoliths are small particles of calcium carbonate in the gel-like membrane layer situated over the sensory hairs (cilia) of the utricles and saccules. When the head moves or is tilted relative to gravity, the inertia of this layer causes it to exert 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.

Besides its involvement in reflex behavior the vestibular system also plays a role in spatial cognition and navigation, i.e., the knowledge of directional heading and location in the environment. Furthermore, recent research has demonstrated that information from the vestibular system also influences heart rate, blood pressure, immune responses, circadian rhythms, and arousal (see Chapter 8). Accordingly, any dysfunction of the vestibular system can potentially induce a number of symptoms including spatial disorientation, postural instability and vertigo, often accompanied by vegetative symptoms such as nausea. It can also involve psychogenic anxiety or panic attacks (Highstein *et al.* 2004).

Astronauts very often experience such sensations of dizziness and disorientation during their first few days in weightlessness. Furthermore, upon returning to Earth after spaceflight, they frequently have difficulty maintaining stable stance and gait, e.g., walking or turning corners in a coordinated manner, and stabilizing their gaze, and (see Clément and Reschke 1996 for review). Their sense of balance and spatial orientation require a period of re-adaptation to terrestrial one-g conditions.

In this respect, their behavior is comparable to that of patients with vestibular disorders, i.e., a pathological condition. In the acute stage of disease, such patients suffer from vertigo and disorientation. In many cases the patients will adapt over a period of several days and vertigo will decrease. Depending on the original cause of the disease, responses may return to normal, or a continuous handicap remain. Thus, the examination of the adaptive behavior of the healthy vestibular system to altered gravito-inertical conditions has provided, and should continue to provide, basic knowledge that is relevant to the clinical situation.

Numerous experiments have demonstrated that the function of the semicircular canals is largely unaltered in prolonged microgravity. Those aspects that are altered are understood to involve the interaction with the input signals from the otolith organs (Clarke *et al.* 2000). Surprisingly, only small disturbances in the control of posture and limb or body movements were observed during spaceflight (see Lackner and DiZio 2000 for review). Given that only a dozen individuals have spent more than six months in space (see Figure 1-11), which corresponds to the current predicted duration of a one-way trip to Mars (see Figure 1-03), there is no conclusive evidence to indicate that prolonged exposure to weightlessness might produce changes to the vestibular system that cannot be reversed. However, we need to refine our diagnostic tools and techniques to examine and even detect those changes which occur over the course of in-flight and postflight adaptation.

There is a limited amount of data on very young rats indicating that the otoconia are irregular in size and distribution following extended periods of weightlessness. These animal studies also suggest plastic central nervous system reorganizations of motor units and their response characteristics, and of cortical maps during spaceflight (Ross *et al.* 1992, 1993, 1994). It would be very adventurous to transfer these observations to the human species. Until long-duration studies are conducted using higher primates in microgravity, the hypothesis of such changes occurring in humans during spaceflight remains speculative.

2 SPATIAL ORIENTATION

Our natural behavior includes sitting, standing, walking, or running, where we are continuously re-orienting ourselves with respect to gravity. Via the vestibulo-spinal reflex mechanisms, the CNS detects such changes in body orientation and initiates the necessary compensatory muscle activity to maintain posture. The brainstem centers involved in this process operate primarily at the reflex level. This process involves integration of information from all contributiong sensors: the eyes, the vestibular organs, and the proprioceptive sensors distributed throughout the body. Whereas information from the vestibular and proprioceptive sensors is coded in internal head and body coordinates, the visual system provides information about our motion and orientation relative to the environment. Hence, visual information is used to match, or "calibrate" the internal with the external frames of reference, i.e., the egocentric information with the exocentric, or external world. At the basic reflex level this is illustrated by the coordination between vestibular and optokinetic reflexes.

2.1 Visual Orientation

The terrestrial environment is rich in horizontally and vertically oriented visual cues (e.g., floors, ceilings walls, buildings, trees). Such horizontal and vertical contours together define a visual frame. The world around us is also polarized, defining perceptual "up" and "down". Visual polarity may be surmised from objects with recognisable "tops" and "bottoms", such as people and trees. Other, more indirect cues reveal the direction of gravity: objects are perceived as lying on the floor, or hanging from a ceiling. Visual frame and polarity together offer a reference frame that strongly influences our sense of orientation (Asch and Witkin 1948, Howard and Childerson 1994). Since we are bound to the Earth, we normally see the environment from a limited range of perspectives. For example, we enter a room through the door in an upright stance, and view the interior from normal eye level.

Accordingly, during their ground-based training, astronauts always view the interior of the spacecraft mock-up from this same perspective. Yet, in space they can assume any body orientation, and view the spacecraft from unfamiliar perspectives (Figure 4-01). This frequently results in strong visual orientation illusions, especially during the early phase of spaceflight (Oman *et al.* 1986, 1988). Such subjective re-orientations may be sudden, and can be triggered by watching a crewmember floating in an inverted position. This view may instantly produce a sensation of being upside-down, a sensation which can be highly nauseating due to the missing vestibular cues for the orientation change.

Visual orientation illusions are aggravated by the complex and inherently ambiguous interior configurations of spacecraft such as the ISS and Mir (Figure 4-04). This has caused significant incidences of spatial disorientation, reference frame issues, and navigation problems among the astronauts and cosmonauts (Young 2000). When Shuttle crewmembers visited the Mir space station, they often became disoriented or lost. This was due to the size and the labyrinth-like nature of the station, and self-rotation of the astronauts producing unexpected visual orientation when floating from one module to another. In fact, the Mir crew's response to the collision with the Progress spacecraft in 1997 was hampered by the fact that they were experiencing cognitive reference frame problems (Linenger 2001). There are also numerous anecdotal reports of operational errors associated with disorientation during ISS crew debriefings. In particular, multiple frames of reference and visual reorientation illusions have caused numerous robotic tele-operation problems for the crew (Young 2000).

Countermeasures directed at spatial orientation problems, as well as training techniques, are clearly required. One promising approach is the use of virtual reality, which offers the possibility to present the spacecraft interior from unusual visual perspectives. It is argued that this facilitates the development of improved spatial memory for the situation (Lackner 1992, Lackner and DiZio 1998a). However, current virtual reality imagery is not powerful enough to override vestibular gravity information and reproduce those visual illusions that occur in flight. It has been demonstrated, for example, that the effectiveness of virtual reality is enhanced by placing the test subject in a supine position, where the vestibular reference to gravity is indifferent with respect to the visually presented orientation. In this situation, subjects experience compelling re-orientation illusions, including a sensation of weightlessness, when watching a visually tilted scene (Howard *et al.* 1997, Howard and Hu 2001, Groen *et al.* 2002). The effectiveness of these methods for familiarization with weightless conditions has not yet been fully explored.

Other mitigating approaches would include evidence-based human factors standards applied to spacecraft architecture and interior configuration as well as signs directing the occupants to exits (Marquez *et al.* 2004). More research is required to understand the extravehicular activities and tele-operational issues. Astronauts operating the robotic arm on board the Shuttle have indicated that it is difficult to relate the three-dimensional information that is concurrently presented to them in several reference frames. Crewmembers from both Mir and the ISS have reported height vertigo (acrophobia) when the Earth appears lower in their field of view, which has proven temporarily disabling for some[1]. There is also concern over the lack of visual reference cues for ISS astronauts performing extravehicular activity operations while the space station is passing through the dark portion of its orbit (Oman *et al.* 1988).

Figure 4-04. Photograph of the interior of the Russian module of the ISS, showing the lack of clear orientation cues. The standard facilities, computers, and spreadsheets are all oriented uniformly. However, the lighting comes from light sources and windows located on both the "floor" and the "ceiling" of the module. Photo courtesy of NASA.

2.2 Sensory Reinterpretation

Apart from these visual inconsistencies, spatial orientation during the flight is further challenged by weightlessness itself. For example, after a couple of angular displacements, free-floating, blindfolded astronauts on the ISS are completely guessing as to what is "up" and "down" (Clément *et al.* 1987, Glasauer and Mittelstaedt 1998, van Erp and van Veen 2006). Without the pull of gravity, the usual contact forces and tactile cues between the body and the supporting surface are absent. Body fluid and internal organs shift toward the head, resembling a prone or supine body orientation (Vernikos 1996). The otolith organs no longer have to detect linear orientations against the prevailing 1-g bias. Deprived of the natural 1-g reference for the definition of head upright, the concept of head tilt becomes meaningless. On the other hand, the semicircular canals continue to code head rotations correctly. Consequently, the normal multi-sensory synergism, above all between gravity sensing and rotation, is no longer operative during head and body movement. Adaptive modification of the related sensory integration in the CNS, or *sensory reinterpretation*, is required to cope with the altered configuration. It can be surmised that visual information becomes more heavily weighted during this process, as evidenced by the increased effectiveness of moving visual scenes to induce sensations of self-motion, or *vection* (Young *et al.* 1986). On Earth, upright observers experience illusions of self-tilt when viewing visual patterns that rotate about a horizontal roll axis (Held *et al.* 1975). However, the effect is limited due to the missing otolith stimulation which would normally accompany the visual tilt. Without the one-g stimulation of the otolith organs, moving visual scenes produce larger effects with shorter latency (Young and Shelhamer 1990).

Another element of sensory rearrangement is that the CNS must consider any otolith input in 0 g as translation of the head rather than tilt. Given that this so-called *tilt-translation reinterpretation* occurs in space, it would follow that a misinterpretation should arise after return to 1-g conditions on Earth. Earlier findings indicated that dynamic body tilt is underestimated postflight, and could even lead to strong sensations of translation (Parker *et al.* 1985). Astronauts report the sensation of being accelerated sideways or forward/backward when they tilt their head in pitch or in roll, respectively, during re-entry and immediately after landing. In general, prolonged exposure to weightlessness affects the sensitivity to linear accelerations, and increases the variability in the detection of accelerations (Young *et al.* 1986, Merfeld *et al.* 1994). This is certainly a contributing factor to the increased postural imbalance and gaze instability observed postflight (Kenyon and Young 1986, Paloski *et al.* 1993).

2.3 Perception of the "Vertical"

Remarkably, weightlessness does not induce a continuous sensation of falling. Nor does the absence of the gravitational vertical completely take away a sense of "upright". Astronauts basically perceive some orientation, which is largely determined by the remaining cues for vertical. As mentioned

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[1] While many astronauts say they've been wowed by the experience of an EVA (extra-vehicular activity, or spacewalk), a few, such as American Jerry Linenger, have confessed to terrible feelings of disorientation. In his memoir, "Off the Planet" (Mcgraw-Hill, 2001) Linenger described a "dreadful and persistent sensation" of falling. "White-knuckled, I gripped the handrail on the end of the pole, holding on for dear life."

above, the visual environment strongly influences spatial orientation in space. In addition, astronauts often report a tendency to perceive the surface below their feet as “floor”, and the surface above their head as “ceiling”, irrespective their actual orientation in the spacecraft. This observation indicates that the main body axis also provides a subjective reference for vertical (Mittelstaedt 1983). Hence, subjective orientation in space results from a weighted sum of the visual vertical and an internal body vertical. Astronauts show differences in the relative weighing between both reference frames, as reflected in individual styles of orientation (Harm and Parker 1993). Moreover, studies in parabolic flight have shown that subjective orientation in microgravity can be modified by visual and tactile cues, cognitive factors, and even by gaze shifts (Lackner and Graybiel 1983, Lackner 1992, Lackner and DiZio 1993). Apparently, the relative contribution of different reference frames is not rigid, but depends on the situation.

An interesting question regarding the issue of spatial orientation is whether artificial gravity can be used to retain some “memory” of gravity. This may preserve basic orientation reflexes that support postural balance after landing on Earth or another planet. Spatially oriented oculomotor and sympathetic functions would also benefit from such approach (see this Chapter, Sections 4 and Chapter 8, Section 6, respectively). To be effective, the artificial gravity stimulus should essentially be perceived as vertical reference, and hence produce tilt responses. Data from the IML-1 Spacelab mission showed that sustained linear acceleration with a gravity gradient ranging from –0.22 g at the head to +0.36 g at the feet (Gz) did not result in sensations of tilt (Benson *et al.* 1997). According to experiments with a short-radius centrifuge on Neurolab, centrifugation at 0.5 g along the Gy or Gz axes did produce considerable tilt sensations of, respectively, lying on a side, and hanging upside-down (Clément *et al.* 2001). Thus we may conclude that the threshold for the perception of the gravitational vertical lies somewhere in between 0.22 g and 0.5 g. Further research should focus on the exact threshold value, and also look into related questions, such as how to orient the astronaut on the short-radius centrifuge and where to place the rotation axis. In order to achieve otolith stimulation, it would be preferable to place the head substantially off-center. Based on the observed variation in visual-vestibular weighting, it can be assumed that the threshold for perceived vertical is also individually determined. Consequently, individual tailoring of the artificial gravity stimulus should be considered.

2.4 Spatial Disorientation during Piloting

Special attention should be paid to the commander who controls the spacecraft during docking or landing phases. It is well known that the human sensory apparatus is principally not suitable to adequately monitor aircraft motions. This creates the risk of spatial disorientation in pilots, which can be described as a false sensation of aircraft motion or attitude with respect to the earth. Spatial disorientation is a common human factor in aviation accidents, such as those designated “controlled-flight-into-terrain” (see Benson 1988, Previc and Ercoline 2004 for review). There is evidence that adaptation to weightlessness makes the commander more prone to spatial disorientation upon re-entry. Flight errors in Space Shuttle landings (e.g., height over threshold, distance, airspeed) were found to correlate with the intensity of postflight neurological symptoms (McCluskey *et al.* 2001). Shuttle pilots recognize the risk that head movements are disorienting, but vehicle accelerations may still lead to vertigo or eye movements (nystagmus) that interfere with instrument readings. In a centrifuge study, pilots refused to fly a real aircraft after exposure to 3 g (Gx) for 1.5 hour (Bles *et al.* 1997).

Clearly, countermeasures should specifically address spatial disorientation problems during phases of piloting the spacecraft. In this respect, there is an interesting development in the field of ground-based spatial disorientation devices. One of such devices features an instrumented cockpit on a six degrees-of-freedom motion-base which can also be centrifuged (Figure 4-06). This facility allows for ground-based studies of the relation between vestibular adaptation to increased gravity levels and the pilots’ control behavior in flight maneuvers that induce spatial disorientation. This approach may be used to train pilots in how to deal with spatial disorientation illusions, and adopt strategies to maintain adequate control of the aircraft despite distracting vestibular sensations. Other systems relate to the use of tactile information to give additional orientation cues to pilots and astronauts (Rupert 2000, Van Erp and Van Veen 2006). In addition, new medications may be tested that suppress vestibular hyper-reactivity as a facilitating factor for spatial disorientation.

Figure 4-05. Desdemona is a sophisticated demonstration, simulation, training, and research facility specified by TNO Human Factors and developed by AMST Systemtechnik (The Netherlands). The subject is sitting in a fully gimbaled cockpit with four cascaded degrees of freedom (360 deg of yaw, pitch and roll rotation, and 2m heave), placed on a longitudinal track (8 m) which is rotated around the vertical axis, adding two synergistic degrees of freedom. Rotation of the track allows centrifugation up to 3 g. Photo courtesy of TNO.

3 MOTION SICKNESS

In association with the above-mentioned motion and orientation illusions, more than 50% of space travelers also experience symptoms of motion sickness during the first 2-3 days in space. Because of the similarity with other forms of motion sickness, it has been designated *space motion sickness*, or *space sickness* (Benson 1977). The cardinal symptoms of motion sickness are stomach discomfort, nausea, and vomiting (Reason and Brand 1975). Other signs include dizziness, increased perspiration, pallor, hyperventilation, decreased appetite, increased salivation, vague discomfort (malaise), fatigue (Sopite syndrome), and depression. Individual responses to the same situation are quite variable. From our comprehensive knowledge with seafarers, we know that in severe situation, however, even the most seasoned sailor will get seasick.

Motion sickness arises in conditions of simulated motion (simulator sickness) and passive exposure to actual motion (e.g., carsickness, airsickness, seasickness). It may also occur in the absence of real motion, for example when watching moving visual scenes in a cinema (cinerama sickness), or computer games (cybersickness). In addition, it occurs in situations where the normal regularities between self-motion and sensory feedback are disturbed, such as when looking through left-right reversing prisms.

3.1 Sensory Conflict Model

The vestibular organs play an essential role in the etiology, since people lacking vestibular functioning do not get motion sick. As a general rule, the onset of motion sickness is triggered by situations where the normal relationship between body movement and accompanying sensory feedback deviates from what the brain would predict based on previous experience. This is the essence of the widely accepted *sensory conflict model*, according to which motion sickness arises as a result of a conflict between sensory inputs about self-motion, and expected sensations (Reason 1978). Illustrative is the observation that carsickness rarely occurs in the driver, but rather the passenger, who is less likely to anticipate the accelerations and turns of the car, especially when there is no view on the road ahead (Griffin and Newman 2004). The driver, however, controls the car motion, and is therefore able to anticipate the sensory feedback. Interestingly, drivers do suffer from simulator sickness when driving in a fixed-base simulator that does not reproduce the corresponding motion feedback. In this case, the sensed motion differs from what the driver anticipates based on his experience in the actual vehicle.

Space motion sickness is often elicited by active head movements in space, in particular pitch and roll (Oman *et al.* 1986). This fits in with the sensory conflict model, since without the 1-g bias the otolith response to head tilt differs radically from the usual response in a 1-g environment. It thus makes sense that roll and pitch movements are more provocative than yaw movements, because the former two would normally involve concomitant otolith stimulation due to the change in head orientation relative to gravity. After several days in weightlessness, head movements are no longer provocative because the CNS has adapted, or recalibrated the vestibular response to account for the absence of gravity. Upon return to Earth, however, astronauts often develop transient motion sickness, much like the *mal de débarquement* experienced by sea travelers on going ashore. Such passengers may have a persistent sensation of motion after return to the stable environment, accompanied by symptoms similar to those of seasickness. This again points out the essential role played by CNS adaptation to altered sensory environments. Thus motion sickness, including space motion sickness, can be considered an “adaptation problem”, i.e., it remains until the vestibular system recalibrates to the new motion environment.

3.2 Centrifuge Induced Sickness

Although the symptoms of space sickness closely resemble those of terrestrial motion sickness, it is remarkable that the commonly used acute motion sickness tests (e.g., cross-coupled Coriolis stimulation, parabolic flights) show no correlation with in-flight incidence (von Baumgarten 1986, Oman *et al.* 1986). Apparently, these short-term tests do not trigger the same causal mechanism that is involved in transitions from 1 g to 0 g. However, there is some indication that space motion sickness can be simulated on Earth by means of prolonged exposure to hypergravity in a human centrifuge. Although the one-hour centrifuge run itself producing a constant gravity level of 3 g (+Gx) was not experienced as uncomfortable, head movements were found to provoke nausea and motion illusions for several hours afterwards. Symptoms of this *centrifuge-induced sickness* (SIC) were rated the same rank-order as during the flight (Ockels *et al.* 1990, Albery and Martin 1994, Bles *et al.* 1997). Furthermore, after the SIC centrifuge run, postural instability was observed similar to the effects observed in astronauts during the first days postflight (Bles and Van Raaij 1988, Bles and de Graaf 1993).

After the SIC centrifuge run, visual motion illusions and motion sickness symptoms are induced by head movements. Similar to in-flight experiences, the intensity of the effects depends on the orientation of the head rotation axis: moving the head out of the vertical (i.e., pitch and roll movement) is more provocative than moving the head about an Earth-vertical (yaw) axis (Bles and de Graaf 1993, Groen 1997, Nooij *et al.* 2004). Furthermore, the effects are more pronounced with the eyes open than with the eyes closed, which also agrees with in-flight reports (Oman *et al.* 1986).

Based on these observations, a refined version of the sensory conflict theory was proposed, stating that motion sickness does not arise from any sensory conflict, but only when the conflict concerns the internal representation of the vertical, i.e., the *subjective vertical*. In this sense, the subjective vertical is determined by integration of sensory afferent information from the visual, the vestibular, and the somatosensory systems on the one hand, and efferent information on planned body movements on the other hand. The subjective vertical theory for motion sickness has been implemented in a mathematical model based on the control of postural balance (Oman 1982, Bles *et al.* 1998, Bos and Bles 2002). The relation with postural balance is understandable since it obviously also requires accurate information of body orientation relative to gravity. The subjective vertical model contains an “internal model” that generates the individual’s expectation of sensory feedback on self-motion and orientation. Current research into the “g-adaptation parameter” in the internal model is in on-going.

The apparent success of the SIC centrifugation paradigm in mimicking space motion sickness makes it suitable to test individual susceptibility of astronauts. It may also be useful for preflight training. It is assumed that it is the gravity-level *transition*, rather than the microgravity environment itself, which causes problems. The idea is that the otolith organs and other, non-vestibular, graviceptors are adapted to the prevailing gravity level. Transition to another gravitational environment, being from 1 g to 0 g or from 3 g to 1 g, brings the system in a mal-adapted state. Until new adaptation is established the orienting responses are inaccurate, and motion sickness may occur. Thus, although microgravity may be unique for the lack of any gravitational reference for vertical, it has in common with other gravity levels that sensory-motor functions become temporarily disrupted due to the transition to a new gravity level. This might also account for the problems during return to Earth gravity. On the other hand there is some indication that, due to the complete loss of the all-permeating gravity vector, microgravity represents a qualitatively different state for the sensory motor, and in fact for all physiological systems.

The issue of gravity-level transitions should be considered an important factor in developing intermittent artificial gravity programs, where astronauts will repeatedly experience gravity-level transitions. An optimal artificial gravity stimulus should therefore retain a memory of gravity, without inducing sickness every time they enter or leave the artificial gravity device. Research should determine the acceptable gravity-level “dose”, which is defined by the combination of gravity level and duration of the artificial gravity stimulus. With the centrifuge paradigm being the only known ground-based test that seems to predict the astronauts' susceptibility to space motion sickness, it offers a tool to investigate such gravity dose value. In a recent ground-based study, a first attempt was made to this effect (Nooij and Bos 2006). This showed that 90 min of centrifugation at 2 g hardly caused any problems afterwards, whereas 45 min at 3 g did provoke space motion sickness symptoms afterwards. Clearly, in-flight artificial gravity levels will be lower than 3 g, but there the transitions are from a baseline level of 0 g. This reduces the signal-to-noise ratio, so that problems may already occur at smaller transitions. This also opens the possibility to study the effect of specific medication against space motion sickness.

3.3 Coriolis Induced Sickness

The most disturbing aspect of centrifugation is probably the cross-coupled angular acceleration detected by the semicircular canals of the vestibular system. As stated above, the function of the canals is to detect angular velocity of the head relative to inertial space for most normal head movements. However, because of their mechanical structure, they fail to register long-lasting constant velocity motion and, instead, indicate that one is stationary in a turn that lasts more than 10-20 s.

When centrifuged subjects move their heads about an axis that is not parallel to the spin axis, two unexpected angular accelerations occur. First, during the head movement a *Coriolis force* occurs, equal to the product of the spin rate and the head velocity that produces transient acceleration about a third orthogonal axis. Second, when the head is turned, the spin angular velocity is moved from one head plane to another, producing a sensation of deceleration about the first axis and acceleration about the second one, the so-called *cross-coupled angular acceleration*. Following this complex stimulation, a sensation of rotation with components around both axes usually occurs for up to 10 s, as the cupulae in the semicircular canals return to their neutral position. This unexpected and confusing sensation is generally accompanied by motion sickness symptoms, a condition often referred to as *Coriolis induced sickness*. However, it is mostly the cross-coupled angular acceleration that is responsible for the confusing sensation and motion sickness. The directions of both the Coriolis force and the cross-coupled angular acceleration depend on the direction the subject is facing in the rotating device, as well as the direction of head movement (see Chapter 2, Section 2.3), thereby complicating the process of general adaptation to the unusual environment.

Notably, the provocative nature of gravity-level transitions, as observed with the SIC paradigm, is essentially different from Coriolis stimulation that happens when making voluntary head movements out of the plane of rotation. Coriolis stimulation causes immediate problems *during* centrifugation, whereas the associated change in gravity level causes problems *after* centrifugation. Remarkably, most research related to artificial gravity has centered on the Coriolis-type of motion sickness, especially in relation to short-radius centrifuges that require high rotation speeds to produce a substantial gravity level (Brown *et al.* 2003, Mast *et al.* 2003, Young *et al.* 2003). Theoretically, Coriolis sickness should not be a problem if the astronauts keep their head still during centrifugation, such as in an artificial gravity sleeper (Lackner and Dizio 2000). However, it is foreseen that the crew activity schedule requires the astronauts to combine their artificial gravity training with other forms of fitness. In addition, it is questionable whether an artificial gravity sleeper would be effective in retaining sensory-motor functions with the astronaut being asleep.

So, most likely, astronauts will have to perform activities during in-flight artificial gravity training. If this is done in short-radius centrifuges, they will have to adapt to high-speed rotations. It has been shown that exposure to a slowly rotating environment, produced by a ground-based rotating room, causes motion sickness for some period of time before adaptation occurs (Guedry *et al.* 1964, Graybiel and Knepton 1972). At rotation rates above 3 rpm, head rotations made out of the axis of rotation were provocative. However, when the rotation rate was increased gradually with small increments, and subjects made head movements during every plateau, they were able to adapt to rotation rates of 10 rpm without ever experiencing symptoms of motion sickness (Reason and Graybiel 1970). Adaptation to higher rotation rates on a rotating chair can also be achieved by exposure to gradually progressing stimuli: a principle generally applied in the desensitization of airsick aviators (Cheung and Hofer 2005).

As mentioned earlier, many adaptation studies have addressed the acute type of motion sickness induced by Coriolis stimulation (Guedry *et al.* 1964, Reason and Graybiel 1970, Clément *et al.* 2001, Brown *et al.* 2003, Dai *et al.* 2003). However, the extent to which a person can adapt to Coriolis stimuli remains undefined. Obviously, desensitization for rotation stimuli will allow the astronaut to freely move his head on the centrifuge. However, it is unlikely that this desensitization transfers to the astronaut's sensitivity to space motion sickness. An important question that remains to be answered is whether it is possible to desensitize astronauts to intermittent gravity level transitions that are inherent to artificial gravity procedures. The ground-based centrifuge paradigm can be suitable to answer this question.

The ability to control susceptibility to motion sickness by adapting the vestibular system is a major advance and has broad application on Earth. Indeed, head movements in a moving or rotating environment such as boats, airplanes, tilting trains (Figure 4-06), and automobiles often provoke symptoms of motion sickness or other discomfort. Also, understanding motor adaptation to Coriolis forces in a rotating environment is relevant for understanding clinical deficits of complex whole body movement on Earth. Finally, the basic understanding of the roles played by vestibular and other sensors in adaptation to unusual environments and the associated disorientation and motion sickness will contribute to astronaut comfort and safety in flight and after landing.

Figure 4-06. The Bombardier Transportation Super Voyager tilting train for Virgin Trains, United Kingdom. Tilting trains are trains the upper part of which, where the passengers are seated, can be tilted sideways. In a curve to the right, it tilts to the right to compensate for the centrifugal force to the left, and conversely. The angle of tilt is determined by the speed of the vehicles, a faster speed requires more banking. Tilting trains can still cause nausea to passengers, as they do not reduce the Coriolis effect. The effect is usually felt under maximum speed and tilt, when the combination of the tilting outside view and lack of corresponding sideways forces can be very disconcerting to the passengers. Optimal tilt is about 50% of the tilt required for full compensation.

4 EYE MOVEMENTS

Eye and head movement are crucial aspects of human visual perception. A reflex called the *vestibulo-ocular reflex* (VOR) coordinates body movements with head and eye movements to provide a stable platform that basically minimize motion blur during self-motion. Other eye movements include gaze shifts (saccades), and visual tracking of a single target (smooth pursuit) or a large visual scene (optokinetic nystagmus). These reflexive eye movements allow stabilization of the retinal image, which is fundamental for object recognition and spatial orientation by enhancing visual acuity. We are unaware of these eye movements, and the visual world appears stable.

Eye movements reflect vestibular functioning in a number of ways. For that reason, eye movement measurement belongs to the standard instrumentation for research and clinical diagnosis of the vestibular patients. This applies equally to the examination of the sensory-motor system under weightless conditions. Otolith-mediated information plays a role in the temporal (time constant) and spatial (three-dimensional) organization of the VOR and the other eye movement responses. However, as will be discussed below, most of the otolith effects are indirect, and require sophisticated recording techniques. Current state-of-the-art video eye tracking equipment facilitates the necessary accuracy and subject-friendly recording of three-dimensional eye movements (Clarke *et al.* 2002), and this technology is available as a standard facility on board the ISS (Figure 4-07).

Eye movement control is affected by changes in gravity level, indicating that these effects are centrally mediated. There is evidence that the VOR during head motion in pitch or roll and the vertical optokinetic nystagmus, which are under the influence of the otolith organs, are disturbed in weightlessness (see Clément 1998 for review). A systematic study of the horizontal, vertical, and torsional VOR during active head movements was performed over the duration of a six-month spaceflight mission. The findings demonstrate that the torsional VOR is radically reduced during prolonged microgravity, with an adaptive recovery during the first weeks postflight (Clarke *et al.* 2000). This can be understood as the effect of removing the otolith-mediated component of the dynamic VOR.

The latency of saccadic eye movements increased, whereas the peak velocities decreased in orbital flight, and the vertical pursuit movements are disrupted. As a result of these changes, astronauts commonly experience *oscillopsia*, i.e., an apparent motion of the visual surroundings, which implies that the VOR is no longer tuned to the head movement. This visual motion illusion might contribute to the genesis of space motion sickness.

Figure 4-07. State-of-the-art DLR Eye Tracking Device currently installed on the ISS as a standard facility for vestibular, visuo-motor and sensory-motor experimentation. The inlay shows the computer display for the online acquisition mode. Based on the CMOS imaging technology, the device permits recording of three-dimensional binocular eye movement, plus head rotation and translation. Sampling rates of up to 200/s are user-selectable. Photo courtesy of Chronos Vision, Berlin.

4.1 Eye Movements during Centrifugation

Changes in eye movements have also been observed under conditions of hypergravity (see Lackner and DiZio 2000 for review). In particular, when an increase in gravity level along the Gz axis elicits a VOR of otolith origin that drives the eyes downward. Attempting to stabilize visually the objects in a fixed position relative to the observer (such as displays in the cockpit) causes those objects to appear to shift upward when the gravity level is increased. Also, tilting the head in pitch or in roll while exposed to an increased gravity level generates a sensation of excess tilt (Figure 4-08). If subjects are attempting to look at a visual target during this motion, vertical VOR will tend to compensate for this illusory excess tilt, and fail to stabilize the gaze on the target.

A false sensation of pitch or roll is also observed during centrifugation when the head is moved out of the plane or rotation. This Coriolis illusion is accompanied by horizontal, vertical, and torsional eye movements that tend to "compensate" for the perceived direction of the stimulus. The *nystagmus* (i.e., the succession of slow and fast eye movements) produced by these head movements is gradually reduced with the repetitions of the head movements (Brown *et al.* 2003, Dai *et al.* 2003). This reduction is retained even after long periods following the centrifugation However, if centrifugation is always applied in the same direction of rotation (clockwise or counterclockwise) the subjects experience after effects in the opposite direction immediately after the rotation stops (Guedry *et al.* 1964).

Nystagmus is also induced by the angular accelerations used in starting and stopping the centrifuge. The repetitive exposure to this type of stimulation is accompanied by a progressive decline in the intensity of the pre- and postrotatory nystagmus, as well as retention of this decline from one session to another, a phenomenon known as *vestibular habituation* (Collins 1973).

Subsequent static tests indicated changes in subjective vertical and sensation of vection (Clément *et al.* 2006). These changes suggest that the habituation of nystagmus and sensation of rotation to this paradigm generalizes to higher, more cognitive spatial orientation reactions.

Figure 4-08. These drawings illustrate the shearing force in the plane of the utricular otolithic membranes when a subject's head in upright or tilted 30 deg off the vertical in a 1-g (upper figures) and 2-g (lower figure) environment (Gz). In the 2-g environment, a 30-deg head tilt elicits a force equivalent to 1 g in the plane of the utricular macula, and the subject may perceive an illusory head tilt of 90 deg. The amplitude of the compensatory vertical eye movements under this circumstance is larger than in 1 g. Adapted from Gillingham and Wolfe (1985).

4.2 Ocular Counter-Rolling

Ocular counter-rolling (OCR) is an otolith-driven orienting eye movement that is generated when tilting (rolling) the head to the side. Typically, the magnitude of OCR is about 5 deg for a 45 deg static head roll tilt. Comparison of the response to static head tilt under 1-g and in-flight 0-g conditions demonstrates that this response vanishes in microgravity (Clarke 1998), although it does re-appear under in-flight, artificial gravity conditions using a centrifuge (Moore *et al.* 2001). Accordingly, this reflex has been used in many postflight studies to gauge the effect of microgravity exposure on otolith function. i.e., after transition from 0 g to 1 g. While the findings of earlier studies are inconsistent (see Moore *et al.* 2001 for review), a more recent study with 14 crewmembers indicated that postflight OCR magnitude is equivalent to preflight values (Clément *et al.* in press). On the other hand, OCR was found to be systematically reduced in subjects who had been adapted to hypergravity, i.e., after 90 min of 3 g centrifugation (+Gx) and transition from 3 g to 1 g (Groen *et al.* 1996). Systematic modulation of OCR has also been measured during the modulation of the gravity level during parabolic flight (Clarke *et al.* 1992) and using a linear acceleration sled on the ground (Merfeld *et al.* 1996).

It has been hypothesized that, under 1-g terrestrial conditions, the natural imbalance (or asymmetry) in otoconial mass between the left-ear and right-ear utricles and saccules leads to differences in the primary otolith signals from the left and right labyrinths. Accordingly, this imbalance is compensated for by the CNS. Upon entry into weightlessness, the otoconial mass no longer deflects the sensory hairs and the neural impulse rate from the left and right otolith organs reduces to a resting rate. However, CNS adaptation to 0-g conditions proceeds with a slower time constant, and during this interval the system will be temporarily uncompensated. This raises the question as to whether (intermittent) artificial gravity exposure would interfere with this adaptive compensation process.

Interestingly, in some spaceflight and parabolic flight studies, the torsional eye position was found to be offset from its preflight position, resulting in binocular disconjugacy (Diamond and Markham 1992, 1998) The authors interpreted this as supporting the *otolith mass asymmetry* hypothesis and its role in eliciting space motion sickness.

In the context of artificial gravity measures it is also relevant to discuss those eye movements elicited by dynamic stimulation of the otolith organs. A comparative study of eye movement responses to active head-to-trunk tilt was performed between 1-g and 0-g conditions during long-duration flights on the Mir space station (Clarke *et al.* 2000). Under 1-g conditions an active head tilt elicits a combined canal- and otolith-mediated oculomotor response. This manifests as a volley of torsional nystagmus beats combined with a tonic OCR. In microgravity, only the transitory canal-mediated torsional nystagmus response remains.

However eye-to-head position and velocity gain, measured after fast-phase elimination and slow-phase reconstruction, was found to be enhanced in 0-g conditions, and to return to baseline after return to normal gravity (Clarke, in press). This is strong evidence that under normal 1-g conditions, otolith and canal contributions are not simply added linearly, but rather that the afferent otolith signal also plays an inhibitory, or stabilizing role in the otolith-canal interaction. The findings obtained from a single-case, longitudinal study over the course of a 400-day space mission indicate that the initially enhanced response is again reduced, over the course of several months, to preflight baseline level. It is hypothesised that in addition to a re-weighting of otolithic afferent information during prolonged microgravity, a corollary inverse re-weighting of neck-proprioceptive afferences provides an effective substitute (Clarke, in press). These findings have some bearing on the velocity storage mechanism discussed in the next section.

4.3 Velocity Storage

Because of the relative short time constant of the semicircular canals to acceleration in the physiologic frequency range of head movement (roughly 0.05-1.0 Hz), the CNS has developed a brainstem mechanism which prolongs the afferent activity (and consequently the VOR) so that it better matches head velocity for a longer period of time. This mechanism is called *velocity storage* because it essentially stores the initial head velocity as transduced by the canals, and maintains it despite the decay in the firing rate of the canal afferent (Raphan *et al.* 1979). It has been clearly demonstrated that the time constant of this velocity storage is influenced by gravity inputs from the otolith organs (Bos *et al.* 2003, Dai *et al.* 2001). Further, the velocity storage time constant has been found to be reduced in microgravity (Oman and Kulbaski 1988, Oman and Balkwill 1993) and after adaptation to hypergravity in a centrifuge (Groen 1997). These findings suggest that the gravito-inertial force level does not alter peripheral vestibular responses to acceleration but does affect central vestibular processing.

Interestingly, the velocity storage mechanism also plays a role in the spatial organization of the VOR and optokinetic nystagmus. In general, the response tends to align to the gravitational vertical on Earth (Gizzi *et al.* 1994). In weightlessness, it was found that this property was still maintained when a steady-state gravito-inertial force was present, such as during centrifugation (Moore *et al.* 2005). Another interesting finding is that there seems to be a close relationship between velocity storage and motion sickness. Using Coriolis stimulation, Dai *et al.* (2003) showed that nausea was greatest in subjects whose eye velocity vector deviated most from gravity. If we assume that the tendency of the velocity storage to align with the spatial vertical relies on, or represents, the internal representation of the vertical, this finding is concordant with the subjective vertical theory on motion sickness. Further evidence of a link between velocity storage and motion sickness lies in the recent finding that Baclofen, a GABA(B) agonist, shortens the time constant of velocity storage and prevents motion sickness symptoms in specific forms of vertigo (Dai *et al.* 2006). All these findings indicate that the velocity storage mechanism is of central importance in the study of the influence of gravity-level transitions.

Quite apart from changes in eye movement responses to vestibular or optokinetic stimulation, recent findings from experiments during six-month missions on the ISS demonstrate that the oculomotor system, in itself, is modified by the loss of the gravity vector (Clarke *et al.* 2005). This is presumably due to a gravity-biased component in the oculomotor control system. This may be related to findings reported by Frens *et al.* (2004) and Reschke *et al.* (2004), which also indicate that the visuo-motor control of eye position is modified by a gravity bias.

5 HEAD AND ARM MOVEMENTS, AND OBJECT MANIPULATION

5.1 Microgravity Environment

Astronauts' anecdotal observations, surveys of video footage, and recent quantitative studies suggest that coordinated movements such as grasping, pointing, and tracking targets (hand-eye coordination) may be degraded during spaceflight. Alterations in arm pointing motions have been reported both during and after spaceflight (Watt 1997, Bock *et al.* 1992). The trajectory of hand-drawn ellipses in the frontal plane in the air with eyes closed revealed a decrease in the vertical length of the ellipses, whereas the horizontal length of the figures was basically unchanged (Gurfinkel *et al.* 1993, Bock *et al.* 2001). Similarly, the vertical size (height) of cubes drawn by hand with eyes closed by astronauts in space was decreased in weightlessness as compared to similar figures drawn on the ground (Lathan *et al.* 2000). Handwriting with eyes closed also showed a decrease in the spacing between characters in the vertical plane in weightlessness (Clément *et al.* 1987).

Rather than an alteration in motor function, due to changes in muscle strength fiber types or innervation, these rapid changes in movement control may be related to alterations in cortical maps of somatosensation. For example, there is a performance decrement in the ability to evaluate the "heaviness" of objects lifted in weightlessness (Ross *et al.* 1986). The perceived position sense of the limbs is also affected, presumably because of a mismatch between muscle length and tension in weightlessness. One Apollo astronaut recalled: "The first night in space when I was drifting off to sleep, I suddenly realized that I had lost track of ... my arms and legs. For all my mind could tell, my limbs were not there. However, with a conscious command for an arm or leg to move, it instantly reappeared – only to disappear again when I relaxed". A Gemini astronaut reported that he awoke to see a disembodied phosphorescent watch glowing and floating in the air in front of his eyes and not even realizing for a time that the watch was his very own, strapped to his wrist at the end of his floating arm (Godwin 1999). All of these examples of alterations in the sensation of body limbs and their motion control as well as the inability to accurately judge object "heaviness" in weightlessness point to a significant alteration in limb proprioception in microgravity (Lackner and DiZio 2000).

Besides sensory and motor dysfunctions, an alternative explanation for the observed changes in weightlessness is that these automated movements were acquired on Earth in the presence of gravity and, when played back in space, still include a "built-in" compensation for a gravitational force that is no longer adequate (Pozzo *et al.* 1998). In support of this hypothesis, astronauts were able to catch balls released from a spring-loaded canon in microgravity, despite the fact that they moved with a constant speed as opposed to a constant acceleration as they would on Earth. However, their timing was a bit off. They reacted as if they expected the ball to move faster than it did, i.e., as if gravity was still present. Yet for nearly fifteen days, the astronauts' brains continued to predict that the balls would be accelerated as if on Earth, even in the face of contrary evidence. Such rigid, inflexible behavior supports the notion that the brain contains a built-in model of gravity (McIntyre *et al.* 2001).

Other experiments performed in parabolic flight (and currently planned for the ISS) have also shown that each new gravitational field is rapidly incorporated into an internal model within the CNS. These internal models are presumably used to predict load forces and generate appropriate grip forces during object manipulation with the hand (Augurelle *et al.* 2003). Indeed, gravity normally provides a constant force acting on the object (depending on its weight) which is adequately taken into account by an appropriate level of grip force. Microgravity, or hypergravity for that matter, presents a significant challenge to dexterous object manipulation because the CNS might involve a greater reliance on visual, tactile and/or memory cues to an object's mass. In addition, there might be over-gripping to reduce the consequence of an erroneous estimate of mass. Alternatively, the hand might initially be moved more slowly than normal to allow more time for feedback-based adjustments to grip force (White *et al.* 2005).

5.2 Rotating Environment

The changes in coordinated movements discussed above, which occur during short-duration spaceflight, are relatively minor but highly systematic and consistent. After a six-month exposure to weightlessness en route to Mars, there is a strong possibility that astronauts may be unable to deal with an emergency situation upon return to a significant (0.38 g) gravitational field if they are unable to control their movements. The astronauts are also unlikely to possess the ability to execute an emergency egress upon landing on the Martian surface. The use of artificial gravity may provide an effective way to avoid these changes in sensory-motor control mechanisms. However, the effects will be quite different using a short-radius centrifuge, where body movements are limited, as compared to the rotation of an entire spacecraft or a large centrifuge inside it, wherein subjects can move around freely.

As discussed in Chapter 2 (Section 2.3), Coriolis forces act on moving objects in rotating environment (Figure 4-09). Consequently, they will perturb head, limb, and body movement. The Coriolis force is proportional to the linear velocity of the imparted motion, the mass of the moving limb, and the angular velocity of rotation. The Coriolis force is transient, i.e., it is absent at the beginning and at the end of a reaching movement, because at those times the linear velocity of the arm is zero. Its magnitude does not depend on the radius of the rotating environment. Therefore it is equally present in both short- and long-radius centrifuges.

The direct consequence of the stimulation of the vestibular system by Coriolis forces and cross-coupled stimulation of the semicircular canals and otolith organs during head movements out of the plane of rotation is motion sickness. In a short-radius centrifuge (see Figure 3-01), head restraint systems can be used to minimize head movements during rotation, which will prevent motion sickness during centrifugation. It has been suggested that, because of the limitation in the ability to perform head, arm or body movements, a short-radius centrifuge would contribute little to the maintenance of sensory-motor calibration of the movement control mechanisms. Consequently, such a device would be unlikely to attenuate the severe disturbance of movements and postural control that present a hazard when landing on Mars (Lackner and Dizio 2000). On the other hand, since changes in proprioceptive inputs may be important to postflight balance disturbances (Kozlovskaya *et al.* 1982), loading the lower extremities using a short-radius centrifuge and simultaneously forcing a subject to maintain balance (via a freely moving backplate for example) could aid crewmembers in retaining terrestrial internal models of sensory-motor integration. If the crewmember could be placed far enough off-axis to sufficiently load the otoliths, then this component of the internal model might also be retained.

Figure 4-09. The Coriolis effect is the apparent deflection of a moving object in a rotating frame of reference. When a subject A throws a ball to another subject B on a rotating platform, it travels in a straight line (dotted line). However, before it reaches B, the platform has rotated and the object passes to the right of the B. To the observer in A, the trajectory of the ball appears to have been deflected to the right by an imaginary force, the Coriolis force.

On the other hand, in a rotating spacecraft or in a large module rotating within it, the crew will be able to move freely. In this environment, however, the Coriolis accelerations will cause deviations in voluntary movements, potentially disrupting performance. If an object is raised from the floor (toward the center of rotation) it will become lighter, and then heavier again as it is lowered back toward the floor (Stone 1973). Similarly, an astronaut walking rapidly in the direction of rotation along the wall (floor!) at the radius of a rotating vehicle would experience an effective increase in body weight due to the Coriolis accelerations and the increase in relative angular velocity. Walking in a direction opposite of the direction of rotation produces the opposite effect, i.e., the astronaut experiences an effective decrease in body weight (see Chapter 2 for the physics explaining these effects). The only direction the astronaut can move and not experience the Coriolis effect is one parallel to the axis of rotation of the vehicle or centrifuge.

As discussed in Chapter 3 (Section 3.1), the pioneering studies on human performance in slow rotating rooms executed in the 1960s showed that for rotation rates above 3 rpm, head movements induced motion sickness symptoms that never fully abated (Guedry *et al.* 1964). The subjects again experienced motion sickness symptoms after the room stopped rotating when they moved their heads. These early experiments involved single exposures to rooms rotating at constant velocities. However, it has since been shown that if the rooms are gradually spun up to their eventual terminal velocity, adaptation to rotation rate of up to 10 rpm with no motion sickness is possible, both during and after rotation (Graybiel and Knepton 1978).

Hand-eye coordination was also affected during these rotating room studies. These adapted gradually with time after continuous exposure. Upon cessation of the rotation of the room, motor performance was again disrupted. In more recent studies it has been shown that if the same reaching movement toward a single target is executed using the same movement pattern over and over again for a number of repetitions, then full adaptation can be achieved in 15-20 reaches (Figure 4-10). It is notable that during the first few reaches in the rotating environment, the subjects felt the Coriolis forces deviating their arm. Interestingly, after multiple reaches, the Coriolis force is not longer perceived by the test subjects, and the movements seemed completely normal. After adaptation to the rotating environment, limb movement feels completely natural and indistinguishable from the normal non-rotating environment (DiZio and Lackner 1995).

Figure 4-10. Trajectory of arm movement reaching towards a previously seen luminous targets at rest before rotation, during rotation at 10 rpm (first trials and after 15-20 trials), and immediately after rotation. Forward arm movements generated rightward Coriolis force during counterclockwise rotation (insert). The curve trajectory reflects the action of the Coriolis forces during rotation. After 15-20 movements, subjects are back to straight and accurate reaching movements despite the absence of visual feedback. Immediately after rotation, the reaches are mirror images of the first trials during rotation. This pattern of adaptation and aftereffects means that the nervous system is precisely anticipating the Coriolis forces and programming motor compensation from them. When subjects are allowed full sight of their limbs during pointing movements, they adapt within 8-10 movements. Adapted from Lackner and DiZio (1997).

Similarly, with repeated head movements, deviations of the trajectory of the head caused by the Coriolis forces and cross-coupled angular accelerations can be restored to normal within 30-40 movements (Lackner and DiZio 1998). Aftereffects in the opposite direction occur post-rotation. However, regular on-board experimenters acquire a dual adaptation to both the rotating room and the normal 1-g environment in the course of carrying out their everyday activities in the slow rotating room. They feel and act completely normal in the rotating room and don’t have aftereffects when the room stops rotating. Recent studies also suggest only minor problems in manipulating and controlling relatively non-massive objects during rotation at rate up to 10 rpm (Lackner and DiZio 2000).

Another aspect related to adaptation to rotating environment is that human intuitions about physics problems are often erroneous. For example, many people erroneously believe that an object that is carried by another moving object (e.g., a bomb carried by an airplane) will, if dropped, fall to the ground in a straight vertical line, when in fact, such an object will fall forward in a parabolic arc (McCloskey *et al.* 1980, 1983). It is argued that people acquire a primitive, non-Newtonian view of the world from their experiences in the world. This view is then revised by using a combination of contextual cues (i.e., more experiences) and relevant knowledge (i.e., more education) (Clement 1982). We have no experience of moving objects in a rotating environment and most subjects are likely to have serious difficulties acquiring intuitions about Coriolis forces and their interaction with centrifugal force and gravity gradient (Figure 4-11). The orientation and motion of the centrifuged subject and the objects with respect to rotation plane and direction will become a new cognitive and perceptual dimension. As pointed out by Hecht (2001), "we have not even started to think about the added perceptual and cognitive load that is required to function in artificial gravity".

In conclusion, ground-based studies indicate that head and arm movements and object manipulation can be adapted to continuous rotation in both short- and long-radius centrifuges. Results obtained recently from experiments in slowly rotating rooms indicate that the 3-rpm limit for adaptation of voluntary movements might be too low. If an incremental exposure schedule is used, then 10 rpm can be achieved. Also, dual adaptation of complex movements to both rotating and non-rotating (1 g) environments may be accelerated with controlled exposure to Coriolis forces and vestibular cross-coupled stimulation. The appropriate adaptation schedule and whether a dual adaptation can also be maintained when astronauts will go back and forth between artificial gravity and microgravity need to be validated during actual space conditions. The cognitive and perceptual implications of artificial gravity also need to be investigated.

Figure 4-11. While inside a slow rotating room, a subject is tossing an object in a trashcan. The trajectory of the object deviates from the straight path due to Coriolis force. This deviation will depend on the direction in which the subject is facing on the centrifuge. Hence, in order to predict object (and its own) motion an accurate spatial orientation is needed. Photo courtesy of NASA.

6 POSTURE AND GAIT

Following from the preceding Sections of this Chapter, it should not be a surprise that balance control and locomotor disturbances have been observed consistently following spaceflight since the earliest missions. The prolonged exposure to microgravity on board a spacecraft has numerous effects on an astronaut's physiology, clearly affecting postural behavior. The anti-gravity function of the core and lower limb musculature is no longer required in 0 g, resulting in adoption of a quasi-embryonic (flexor posture) attitude. Early in-flight many try to minimize head movements to reduce visual and orientation illusions as well as provocation of space motion sickness (see this Chapter, Section 3). Initially many are more comfortable and efficient when orienting themselves to the visual vertical contours of the modules (corresponding to their orientation during training), but over time (and presumably after adaptation to the new environment) they more freely assume whichever orientation is most convenient. These behavioral changes reflect adaptive responses necessary to optimize sensory-motor performance in the new environment, and, as with other sensory-motor/behavioral learning, practice tends to improve the performance and make the behaviors permanent. Unfortunately, upon return to Earth the sensory-motor programs developed to optimize performance in space are no longer optimal. Thus, terrestrial sensory-motor control programs must be reacquired through processes requiring hours to weeks to be completed.

Postflight balance control deficits resulting from in-flight sensory-motor adaptation to 0 g were predicted early on as a potential operationally-important side effect of spaceflight. In 1965, Graybiel and Fregly (1965) introduced a "rails test", which was subsequently used to demonstrate balance control deficits in U.S. crewmembers returning from orbital missions. Also during the 1960's, Roberts (1968) introduced the concept of a labyrinthine-generated "behavioral vertical" to explain a critical role the vestibular apparatus plays in providing a dynamic internal reference frame for neuro-motor control of upright stance (see Section 1 of this Chapter for more information), and in a series of symposia on the role of the vestibular organs in the exploration of space (Graybiel 1965, 1966, 1968, 1970, 1973), a number of investigators presented data demonstrating the confluence of multi-sensory information in the vestibular nuclei and the cerebellum (see Section 2.2 for more detail).

Since those days our understanding of terrestrial balance control has progressed rapidly. In parallel, numerous spaceflight investigations have contributed to our understanding of the characteristics, demographics, and mechanisms underlying the transient disruption of balance control following spaceflight. Human studies of integrated balance control performance, neuro-motor reflex function, proprioceptive function, and visuo-perceptive function have been performed. Animal studies of remodeling in the cerebellum and vestibular end organs have also been performed.

Today postflight decrements in posture and gait control have been well characterized from both basic science and occupational health perspectives. Early after flight postural stability and locomotor control are disrupted in all crewmembers. The degree of disruption decreases with increasing spaceflight experience (number of previous flights), but increases with mission duration. As mission duration increases there is also an increased incidence of postflight autonomic system problems. For example, orthostatic hypotension, which can exacerbate the balance control deficits, may result in part from vestibular autonomic system alterations.

6.1 Role of Gravity

That the central nervous system uses gravity-related sensory inputs as a fundamental reference for spatial orientation and balance control is not immediately obvious from observing posture and gait behaviors in everyday life. However, by observing the debilitating effects of vestibular disorders on posture and gait or by closely observing the behavioral patterns of normal individuals performing at or near their limits of stability (Figure 4-12) it becomes more obvious. So, by learning during spaceflight new sensory-motor programs that allow one to orient, navigate, and move about effectively without gravity, the CNS learns to overcome (eliminate?) its dependence on a fundamental physical orientation reference.

It is of interest, therefore, to examine in detail the postural behavior of astronauts immediately after spaceflight, during the time that they must recalibrate their equilibrium systems to the 1-g environment. While the severity and duration of the postflight behavioral responses varies widely from person-to-person, ranging from complete ataxia to only subtle effects, all returning crewmembers have observable behavioral changes. Most adopt a wide stance (and gait) with their feet farther apart than normal. Initiating and, more noticeably, terminating gait appear to take more effort and generally result in body oscillations that give the impression of compromised stability. Many minimize head movements and some move their head-trunk segments *en bloc*, presumably to avoid disorientation, instability, and motion sickness. Most have difficulty controlling the trajectories of their centers-of-mass, particularly when negotiating corners: often they make very wide-radius turns but sometimes they clip turns short. Many report unusual perceptions while climbing stairs, often that they feel more like they are pushing the stairs down than like the stairs are propelling them up. When standing still, many long-duration crewmembers exhibit co-contractions and occasionally tremor in their lower limbs, but when sitting down, their leg muscles appear to be without tone, literally hanging off their bones.

Figure 4-12. Illustration of the reliance of the central nervous system on using gravity as a fundamental spatial orientation reference indicating Earth-vertical. Notice how despite the highly unusual (and unstable) posture being assumed by this golfer, he manages to maintain his head orientation along the gravity vector. This photograph appeared in the Portland Oregonian newspaper on October 2nd, 2002 (source unknown).

Quantitative assessment of postflight posture and gait disturbances began with the first human spaceflights. As noted above, in the U.S. Apollo and Skylab programs, investigators used a sharpened Romberg test, performed while standing on rails of various widths, to quantify deficits and track recovery (Homick and Reschke 1977). Later investigators introduced various postural perturbation tests (Kozlovskaya *et al.* 1983, Clément *et al.* 1985, Kenyon and Young 1986), postural reflex tests

(Kozlovskaya *et al.* 1982, Reschke *et al.* 1986), gait coordination and locomotor performance tests (Bloomberg *et al.* 1999), and more sophisticated tests designed to elucidate the roles of specific sensory systems in the observed postural deficits (Bles and de Graaf 1993, Paloski *et al.* 1999). The results all point to underlying causes expected from the arguments presented throughout this chapter: CNS reinterpretation of vestibular information seems to be the primary driver of postflight posture and gait disturbances following short-duration missions, but as mission duration increases somatosensory and motor control system adaptation seems to play an increasingly important role. The exact mechanisms of this slower phase of in-flight adaptation are not yet well understood.

An on-going, long-term quantitative study of postflight balance control performance uses a clinical computerized dynamic posturography system (Figure 4-13). This system cleverly employs "sway-referencing" to reduce or disassociate visual and ankle proprioceptive information from Earth-vertical (Figure 4-14), making it possible to isolate the role of vestibular information in the highly integrated sensory-motor balance control task. Results from this study have been useful in characterizing the amplitudes and recovery time courses of the postflight balance control deficits (Figure 4-15). They have also demonstrated that the postflight deficits of experienced astronauts are less severe than those of novice astronauts, primarily because experienced astronauts seem to have learned how to better use vestibular information early after landing, and that the initial deficits in balance control become far more profound and persist much longer as mission durations increase from two weeks to six months.

Figure 4-13. Computerized dynamic posturography system (EquiTest, NeuroCom International, Clackamas, Oregon, USA).

Figure 4-14. Schematic representation of the six sensory organization test conditions. Note that tests 5 and 6 artificially disrupt visual and proprioceptive information, forcing the system to rely on vestibular information as the sole veridical source of vertical reference information.

6.2 Effects of Artificial Gravity

Artificial gravity may have a salutary effect on postflight posture and gait disturbances. Standing, as such, is of course not possible without mechanical aids, such as bungee cords, on board present spacecrafts. While bungees can putatively provide sufficient loading to reduce anti-gravity muscle atrophy and bone demineralization during extended exposure to 0 g, they can result in unnatural loading of the body and new sensory-motor coordination programs for maintaining posture and gait. Also, while they can maintain loading of lower limb proprioceptors and exteroceptors, and require integration of those receptors into sensory-motor control schemes, they do not load the otolith organs, nor do they provide hydrostatic loading of the cardiovascular system. Artificial gravity, on the other hand, being an inertial load could stimulate bone, muscle, sensory, and cardiovascular systems in much the same way that gravity does. Depending on the artificial gravity configuration, however, additional (non-gravitational) loading associated with Coriolis forces and semicircular canal stimuli associated with cross-coupling could offset these salutary effects.

In Section 5 the theoretical considerations for moving about in a rotating spacecraft are described. How this may affect gait and posture remains unknown, since it has not yet been experienced by astronauts. An indication of the effects can be experienced on Earth by walking radially outwards on a spinning carousel. The inertial acceleration generates a sideward force (Coriolis force), according to Newton's second law, and the subject must counter that unexpected force to avoid losing balance or taking a path that is curved relative to the carousel (see Figure 2-06). As noted in Section 3.3, however, subjects exposed to similar Coriolis forces on board a slow rotating room were able to learn how to effectively move about in that environment after a few days of exposure. Additionally, anyone trying to walk along the rim of a spinning vehicle in the direction of the spin is subject to a radial inertial acceleration inward, which generates a downward Coriolis force, making the space walker feel heavier. If the astronaut were to turn around and walk along the rim in the direction opposite to the spin, the Coriolis force would be directed upwards and the weight of the astronaut would be reduced (see Chapter 2, Section 2.3). This is not a condition that can be reproduced on Earth.

The only human studies of gait and balance changes associated with prolonged continuous rotation come from the multi-day rotating room experiments performed in the 1960's (see Chapter 3, Section 3.1). These demonstrated that posture and gait were disrupted to about the same extent at the beginning of the exposure to the rotating environment and after returning to the terrestrial environment (Graybiel *et al.* 1965). The magnitudes and time constants of the observed disruptions were similar to those observed in crewmembers returning from short-duration spaceflight missions.

The first comparison between the effects of spaceflight and intermittent centrifugation on posture and locomotion was carried out on three European science astronauts. These astronauts were tested immediately after their return to Earth from a Spacelab mission (Bles and Van Raaij 1988) and, a few years later, after a 3-g (+Gx) exposure in a centrifuge for 1.5 hour (Bles and de Graaf 1993). After the spaceflight, the astronauts were tested in a room that could tilt sinusoidally in roll with a peak amplitude of 5 deg at frequencies of 0.025, 0.05, 0.1, and 0.2 Hz. The subjects stood on a fixed-base stabilometer platform beneath the floor, i.e., only the visual surround was tilted. On the first day, one of the astronauts was completely visually dependent, swaying together with the room. However, he was back to normal on the second day. Interestingly, he experienced the room and the platform as stationary, his weight shifting from one foot to the other (subjects who do not perceive the room as moving normally perceive the platform as tilting). The other astronauts could remain upright, but only with considerable effort. The general impression here is that postural movements were limited to an inverted cone after the spaceflight, the aperture of the cone growing wider every day. Getting out of that cone was considered to be provocative to motion sickness and had therefore to be avoided. The study also revealed that the subjects tried to minimize head movements as much as possible, by turning head and trunk together.

Some years later the same astronauts participated in an experiment at TNO and at the Aeromedical Institute in Soesterberg where they were exposed to 3 g on a centrifuge (Gx) for 1.5 hour (see also this Chapter, Section 3.2). After the centrifuge runs, their postural behavior in the tilting room was similar to that observed after spaceflight (Bles and de Graaf 1993). Associated signs were the destabilizing effects of head movements on posture and gait. Accordingly the subjects walked very carefully, trying to minimize head movements as much as possible. Illusory motion perception was reported ("floor motion"), for instance when they climbed the staircase out of the centrifuge pit. Results of studies on many subjects indicate that some of the subjects recovered quickly within 2 hours, but the majority suffer from this sickness-induced centrifugation paradigm for many hours. However, adaptation is faster if they move around, and make head movements instead of remaining motionless. Convincing the subjects to move around, and being nauseated but adapting faster, is not easy.

Other studies of physiological responses to intermittent gravity have been performed in ground-based laboratories, but most have targeted cardiovascular responses (Iwasaki *et al.* 2001, Iwase *et al.* 2002, Evans *et al.* 2004) or motion sickness responses (Young *et al.* 2001, Hecht *et al.* 2002). Intermittent rotating room studies discussed in Section 5.2 provide some insight into per- and post-rotatory adaptation of body segment movements related to posture and gait. Very recent evidence is being generated by a study being performed with subjects deconditioned by 21 days of head-down-tilt bed rest to simulate spaceflight. Subjects in the treatment group are exposed to daily 1-hour artificial gravity therapy on a short radius (<3 m) centrifuge (Gz stimulation: 2.5 g at the feet-support interface and 1 g at the heart level). For the first seven subjects, the incidence of motion sickness symptoms has been very low, and the post-bed rest effects on posture and gait have been unremarkable, in part, because bed rest has little effect on the vestibular system. These preliminary results are promising, but, clearly, there is a need for more integrated physiology (sensory-motor, cardiovascular, muscle, at least) studies of intermittent artificial gravity before we can fully understand its effects on posture and gait

Figure 4-15. Balance control loss and recovery from 13 crewmembers following short-duration (4-17 days) spaceflight missions. The Composite Equilibrium (EQ) Score *is a weighted average of the computerized dynamic posturography performances measured using the six sensory organization tests shown in Figure 4-14. Adapted from Paloski et al. (1999).*

7 CONCLUSION

The present review of current data indicates that the vestibular system is intimately linked to the question of the efficacy of using artificial gravity as a countermeasure during spaceflight. A number of observations demonstrate that we still have much to learn about vestibular and CNS reactions to the application of an artificially generated linear acceleration. These include oscillopsia, an erroneous sensation of translation when tilting the head, motion sickness symptoms, inappropriate eye movements for any given head motion, and uncoordinated limb movements.

Few studies have been performed on the effects of long-term exposure to microgravity on the vestibular system. Only recently have the necessary facilities been made available on board the ISS, and the first systematic studies commenced. Consequently, there is currently insufficient experimental data available to identify a beneficial prescription for artificial gravity for the sensory-motor system (or for the other physiological systems, see the following chapters) for long-duration space missions. Priorities must be given to research establishing the parameters, such as centrifuge radius, rotation rate, duration, and repetition rate of artificial gravity sessions, which prove effective for maintenance of musculo-skeletal and cardiovascular condition while remaining compatible with the neurovestibular system. Knowledge gathered from medication studies as well as from adaptation mechanisms in patients suffering acute vestibular lesions may provide additional information that might help to set up the appropriate stimulus paradigms.

Considered as a neurovestibular countermeasure, artificial gravity is a double-edged sword. While it might be employed usefully for pre-adapting crewmembers to planetary gravity, it may well introduce problems with spatial orientation, vestibular conflict, and motor and postural disturbances (cf. Lichtenberg 1988). In a typical scenario, with a 2-m-radius human centrifuge rotation at above 60 rpm is necessary to produce an artificial gravity level of 1 g or greater. In such a device, when the astronaut attempts to move the head or limbs out of the plane of rotation, the Coriolis forces on the inner ear organs and on moving limbs would induce spatial disorientation, non-stabilizing compensatory eye movements, loss of coordination, and motion sickness.

It is possible that the sensory-motor system would adapt to repeated artificial gravity exposure, as has been observed in comparable conflicting conditions on Earth. However, assuming that the centrifuged astronauts adapt to motion sickness, motor recalibration, and neurovestibular side effects, cognitive adaptation to this complex environment will remain a challenge. Perhaps this is the price to pay for a countermeasure that, on the other hand, could result in long-term stabilization of bone demineralization and cardiovascular deconditioning. Clearly, an interdisciplinary approach is necessary to research this complex area. It would appear that the current ground-based bed rest studies are not fully adequate for this purpose. Although useful for the examination of cardiovascular, muscle, and bone deconditioning, the bed rest paradigm is unsuitable for the study of sensory-motor problems since the predominant 1-g vector remains as a central reference of the orientation senses. Since the sensory-motor issues seem to be more related primarily to transitions between gravity levels, testing under ground-based hypergravity (centrifuge) and hypogravity (parabolic flight) conditions is likely to provide more relevant information for their solution.

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