# Spatial Orientation, Adaptation, and Motion Sickness in Real and Virtual Environments

Reason and Brand (1975) traced the first written report of sea sickness to Hippocrates, 2400 years ago. They also noted that motion sickness occurs in many situations involving either passive body motion or active interaction with the world via indirect sensorimotor interfaces (e.g., prism spectacles). The best advice for avoiding motion sickness in such situations (without medication) is to refrain from moving your head, to keep your eyes closed, and to move as economically as possible. This must sound hopelessly restrictive to anyone contemplating virtual environment (VE) systems in which users may play an active part, computers and specialized displays are the user's interface to the world, and the experienced world may purposely not correspond to the actual world. As might be expected motion sickness is being reported in VEs that involve apparent self-motion through space, the best known examples being flight simulators (Kennedy, Hettinger, & Lilienthal, 1990). The goals of this paper are to introduce motion sickness symptomatology, to outline some concepts that are central to theories of motion sickness, spatial orientation, and adaptation, and to discuss the implications of some trends in VE research and development.

## 1 Motion Sickness Symptomatology

The signs and symptoms of motion sickness include nausea and vomiting, cold sweating, pallor, salivation, drowsiness, dizziness, headache, eye strain, lethargy, lack of initiative, and chronic fatigue. These indices appear with various severities and in different combinations depending on the exposure conditions and the individual. Almost all systems for rating symptoms and calculating motion sickness severity rely on subjective observation and self-report (e.g., Graybiel, Wood, Miller, & Cramer, 1968). Monitoring physiological correlates of motion sickness (e.g., electrogastrograms, cardiopulmonary function, phasic skin conductance, and peripheral blood flow) has proven helpful for understanding the physiology of motion sickness under laboratory conditions but is insensitive, nonspecific, unreliable, and/or restrictive under operational conditions (Cowings, Suter, Toscano, Kamiya, & Naifeh, 1986; Golding, 1992; Graybiel & Lackner, 1980; Lawson & Lackner, 1992; Stern, Koch, Leibowitz, Linblad, Shupert, & Stewart, 1985; Sunahara, Johnson, & Taylor, 1964). In flight simulators (Kennedy, Lilienthal, Berbaum, Baltzley, & McCauley, 1989) and in our psychophysical experiments that involve real or apparent body motion (e.g., Lackner & Texiera, 1977), it is uncommon to observe severe symptoms—extreme nausea or vomiting, the skin appearing white as a sheet, and the clothes being soaked with perspiration. But close observation may reveal that the subject's upper lip or palms are damp, swallowing is frequent (stomach discomfort and increased salivation), and he or she is unresponsive (eye strain, drowsiness, lack of initiative) and complains of headache and fatigue. Drowsiness or a feeling of "spaciness" is sometimes the sole symptom and can disrupt the remainder of a day's work. This has been dubbed "The Sopite Syndrome" by Graybiel and Knepton (1976). Eye strain, headache, and dizziness and fatigue are the most likely symptoms to be associated with viewing a wide-field visual display depicting body motion through the environment (Kennedy et al., 1989, 1990; Lackner & Texiera, 1977); nausea, salivation, pallor, and sweating usually follow a period of unusual, prolonged, or intense linear and angular acceleration, especially if head movements are made (Johnson, Stubbs, Kelks, & Franks, 1951). The former set of symptoms will likely prevail in VEs, which will probably exclude intense accelerations.

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These signs and symptoms can appear within minutes of acute exposure to a nauseogenic environment or take hours, and they can disappear within minutes after exposure ends or persist for hours. Symptoms usually abate if exposure to the stimulus is prolonged but often re-emerge upon return to normal conditions (Graybiel, Kennedy, Knoblock, Guedry, Mertz, McLeod, Colehour, Miller, & Fregly, 1965).

## 2 Motion Sickness and Sensorimotor Rearrangements

There are few principles that predict whether a situation will bring about motion sickness or what particular signs and symptoms will be involved. Sensory conflict models have been proposed to explain some of the facts concerning the relationship between control of orientation and motion sickness. In general, they assume that the central nervous system is able to generate expectations of the patterns of vestibular and other sensory feedback appropriate for intended voluntary body movements. Sometimes a "neural model" of the current physical environment (Reason & Brand, 1975) or of the physiological control system itself (Oman, 1982) is explicitly proposed for producing such an expectation. If sensory feedback associated with voluntary movement does not match expectation because of transport in a vehicle or because a sensorimotor rearrangement (e.g., reversing prism spectacles) has been introduced, a conflict signal is generated that ultimately produces symptoms. For example, moving the head while wearing prism spectacles that reverse or invert objects in the visual field elicits motion sickness symptoms and visual illusions and impairs control of voluntary movement; moreover, during continued exposure, the motion sickness abates at about the same rate that perceptual and motor errors diminish (Gonshor & Melvill Jones, 1976; Stratton, 1897).

Inverting prisms lead to the following rearrangements in the relationship between movement and sensorimotor feedback: one must raise one's head to direct gaze toward an object seen as down; during elevation of the head, optical flow is upward relative to the head, which is opposite to what would normally occur for the actual inertial motion; the correlations among visual, auditory, and proprioceptive information from an object that can be seen, heard, and touched are systematically altered; the eyes and head will assume new tonic postures relative to the head and torso, respectively, because of changes in the visual horizon, altering their habitual relationship to the gravitoinertial field.

Sensory conflict theories do not predict which of these sensorimotor rearrangements will generate conflict signals and which will not, nor do they help quantify the magnitude of conflict. They do not even help in developing a comprehensive list of potentially relevant sensorimotor rearrangements because this depends on understanding spatial orientation at many levels of analysis. Conflict theories actually restate the obvious, that sensorimotor rearrangement is correlated with self-limiting motion sickness and degradation of orientation control, and beg the important questions of identifying normal versus abnormal sensorimotor relationships.

Sensory conflict theories embody the notion that specific movements are associated with single, fixed relationships between sensory and motor signals. Several investigators have criticized this approach with regard to theories of movement control in general (Bernstein, 1967; Lackner, 1981). Multiple levels of analysis are necessary for investigating spatial orientation, adaptation, and motion sickness. These include describing organism–environment interactions in optical, mechanical, and acoustical terms (cf. Gibson, 1966) and understanding specific sensory and effector systems as well as specialized sensorimotor subsystems such as the vestibulo-ocular reflex. Abstract representations of terrestrial conditions that constrain perceptual mappings of afferent and efferent signals are also essential. Real environments and VEs may be nauseogenic because of sensorimotor rearrangements that are disruptive to one or more of these layers of orientation control, and individuals may differ in the operation of the layers and thus in susceptibility to different "environments."

An organism's spatial orientation systems are calibrated in the sense that they transform patterned sensory and motor signals into dynamic information about the environment and the self in dimensions and units appropriate for accurate perception and coordinated action. That is, spatial orientation systems instantiate transformational computations and solve for the parameters appropriate for the current gravitoinertial force, optical, and acoustic background. This can be simplified for the nervous system by the imposition of geometric and dynamic constraints that match, to the extent possible, regularities of organism–environment interactions. For example, our spatial orientation systems are normally calibrated to the constraint that the visual background is fixed relative to the substrate of support and inertial space. An organism living in a medium more dense, opaque, and textured than air cannot use this constraint. VEs can be generated that violate such terrestrial constraints. Identifying which of the many existing terrestrial regularities actually serve as constraints for spatial orientation systems is an empirical matter, not one that can be predicted from current theories.

In summary, the following working hypotheses will guide our considerations about motion sickness in VEs:

1. Optical, acoustical, and mechanical energy acquires spatiotemporal structure that, within constraints, is functionally related to organism–environment interactions.
2. Spatial orientation systems map this structure onto perception and control of orientation.
3. Spatial orientation systems are normally calibrated to terrestrial constraints but can adapt to violations of these constraints.
4. A sensorimotor rearrangement may be said to exist when the organism or environment changes so that familiar interactions structure energy in unfamiliar ways, when sensorimotor systems are disrupted or forced to work outside normal parameters, or when there is a violation of the constraints to which adaptation has currently calibrated the spatial orientation systems.
5. Motion sickness and spatial disorientation will be associated with sensorimotor rearrangements until adaptive recalibration occurs.

## 3 Motion Sickness and Sensorimotor Rearrangements in VEs

Long-standing observations indicate that sensorimotor rearrangements that disrupt control of head movements are potent etiological factors in motion sickness (James, 1882; Johnson et al., 1951; Purkinje, 1820). Despite the limited and inchoate theories of spatial orientation that exist, it is possible to make some predictions about motion sickness in VEs. First, motion sickness will be a problem both in the early stages of development and integration of VE systems as well as later when "ideal" systems exist. We will argue that this is due to unintended sensorimotor rearrangements in current VE systems but that ultimately we will want to design systems that generate virtual events that would be nauseogenic even if they were real, for example, aircraft flight and amusement park rides. Second, head-mounted devices (HMDs) for displaying information and sensing movement are (and will be for the foreseeable future) an integral part of most VE systems. The mass of HMDs is a source of sensorimotor rearrangements during head movements and is likely associated with some motion sickness. Third, we will introduce the notion that devices such as centrifuges, treadmills, and six-legged synchronized motion bases are gravitoinertial VE displays. Such displays are not consistent with a philosophy of developing inexpensive systems that can be reconfigured in software; however, excluding them from VEs in which the experience of body motion is desired will result in sensorimotor rearrangements. The other horn of this dilemma is that including gravitoinertial VE displays can be problematic because it is difficult to simulate gravitoinertial force environments that are different from natural terrestrial conditions. Moreover, simulations may be valid only for a user who remains motionless, and adding a mass (such as an HMD) to moving body parts will exacerbate this problem. Finally, understanding human adaptation to altered gravitoinertial force environments and designing VEs sensitive to human adaptive abilities may help solve some of the problems, and monitoring motion sickness can provide information for achieving this.

### 3.1 Motion Sickness in Current and Future VEs

Zeltzer (1992) has proposed a system for characterizing VEs along three dimensions—autonomy, presence, and interaction. Autonomy refers to the simulation of knowledge and volition in computational models of objects within the VE. Presence is the feeling of immersion in the VE, which depends on "the degree to which input and output channels of the machine and the human participant(s) are matched" (Zeltzer, 1992). Zeltzer argues that current VE systems are not well matched, as demonstrated by limitations in the sense of presence. This is analogous to our assertion that sensorimotor rearrangements in current VEs will be evinced by the evocation of motion sickness. Complete and formal definitions of "matched" and "sensorimotor rearrangement" depend on a basic understanding of human sensorimotor control, so both ideas must be recognized as empirically based working hypotheses, the refinement of which will lead to a deeper understanding of human sensorimotor control and to more ideal VEs.

The third characteristic dimension of VEs, interaction, refers to the real-time computation of a VE's state based on user actions. Even if perfectly "matched" individual displays were available, interaction would currently be limited by the variables we choose to sense (e.g., head velocity, gaze direction) and to control (e.g., visual perspective, shading) and the power of the programs and computers used to accomplish the necessary transformations. For example, in current VEs there are temporal and geometric distortions in visual perspective, shading, etc., contingent on a translational head movement because the visual displays and head tracking devices do not match human capabilities and graphics systems cannot keep up with rapid human movements. This generates a significant set of sensorimotor rearrangements, similar to wearing prism spectacles, and leads to motion sickness, perceptual and motor errors, and ultimately to adaptation.

In the future, algorithms, computers, and interfaces will improve vastly and motion sickness will likely be avoided in the VEs described above. However, we will want to generate VEs that would be provocative if they were real. A major thrust of VE research and development is to generate a convincing experience of movement within a large space during confinement to a VE system of limited volume. As alluded to above, some real movements involving passive transport are provocative, so ideal virtual experiences of such movements will likely be provocative as well. This has already been seen in well-developed VEs such as in Disney's "Star Tours" (personal experience) and in some advanced flight simulators (Kennedy et al., 1989, 1990). Deficiencies in the VEs are certainly to blame for some of this, but, on the other hand, a perfectly veridical VE would include the same experience of motion sickness that would be evoked in the real environment. This may even be considered desirable in terms of training pilots to recognize the specific maneuvers that will be provocative and how to work through them if they cannot be avoided. The sources of sensorimotor rearrangement in such VEs will be discussed further below.

In summary, current VEs generate nauseogenic sensorimotor rearrangements because of hardware and software limitations; future systems may be nauseogenic because improved technology will allow the accurate presentation of environments containing sensorimotor rearrangements as an integral part.

### 3.2 The Role of HMDs in Motion Sickness

Making head movements in moving vehicles or with altered visual feedback has long been recognized as nauseogenic (Stratton, 1897; Johnson et al., 1951). Because individuals who lack vestibular function are insusceptible to motion sickness (James, 1882; Graybiel & Johnson, 1963; Money & Friedberg, 1964), attention has focused on conditions that affect vestibular function as causal factors in motion sickness. For example, investigation of space motion sickness concentrates on changes in otolith function due to the null gravitoinertial force background, otolith-mediated alterations in other orientation subsystems, and rearrangements of the normal correlations among signals from the otolith organs, semicircular canals, and vision (Parker, Reschke, Arrott, Homick, & Lichtenberg, 1985; Mittelstaedt, 1988; Kornilova, Yakovleva, Tarasov, & Gorgiladze, 1983;

Reschke, Anderson, & Homick, 1984). However, gravitoinertial force that affects the inner ear also determines the effective weight of the head. Altered head weight rearranges the relationships among motor commands and the cervical joint, tendon, and muscle afferent feedback contingent on head movements. We have performed experiments in the weightless and high force phases of parabolic flight, and in the laboratory with weighted helmets, which independently manipulate vestibular stimulation and nonvestibular sensorimotor control of the head and neck (Lackner & DiZio, 1989a, 1991, 1992). In one study, subjects exposed to periodic angular accelerations and decelerations in a revolving chair became more severely motion sick if they were wearing a helmet that had 600 g weights attached near the ears than with no unusual load on their head (Lackner & DiZio, 1989a). The effective weight of the head is a significant, independent etiological factor in motion sickness and it affects perceived movement in predictable ways.

Increasingly, HMDs weighing 2.5 pounds or more are becoming the prime display of VE systems. These systems increase the effective weight of the head by 20% or more, increase the effective inertia by a greater amount because of the mass distribution of the display, and sometimes shift the effective center of mass of the head altering static and dynamic balance. Our observations indicate that simply moving about wearing a device with this mass distribution elicits symptoms of motion sickness.

### 3.3 Gravitoinertial VE Displays

Active locomotion and some forms of passive transport are not nauseogenic but it will be very difficult to create ideal virtual experiences of such movements. This is because of the difficulty in stimulating the user with the gravitoinertial forces that would be present if movement were actually taking place in the way simulated by the visual, acoustic, and haptic displays. Gravitoinertial force is the vector sum of Earth's gravity and other forces that change a body's linear velocity relative to the Earth. To some extent, inertial linear accelerations, tilt relative to gravity, and centrifugal accelerations generated by rotating devices are perceptually interchangeable (cf. Guedry, 1974). Thus, variable speed treadmills, six-legged synchronized motion bases, and multiaxis centrifuges may be considered gravitoinertial VE displays. The vestibular apparatus and other mechanoreceptors are very sensitive to the body's dynamics so lack of gravitoinertial fidelity in VEs will be a significant etiological factor in motion sickness. There are several ways in which gravitoinertial fidelity may be restricted.

### 3.4 Sources of Sensorimotor Rearrangements from Gravitoinertial VE Displays

Multiaxis centrifuges and six-legged synchronized motion bases can simulate a small number of dynamic gravitoinertial force backgrounds for specific aircraft, at great expense. Developing a virtual ground surface, like a treadmill, that would deliver forces consistent with locomotion through space is a significant challenge (see below). Thus, one approach would be to exclude gravitoinertial displays from VEs for generating the experience of body motion. In the case where visual and auditory VE displays present the dynamic scenes and noises that would be present if the body were moving through space, the lack of inertial acceleration would constitute a sensorimotor rearrangement. It is quite common for motionless people in psychophysical experiments to become ill while viewing a moving scene and experiencing self-motion (Dichgans & Brandt, 1972) and it will probably also become more common in VEs as visual displays improve.

At best, current gravitoinertial VE displays generate only a subset of the gravitoinertial forces that would actually be present during real movement of the type being depicted or sounded out by the other VE displays; often spurious conditions that would not be present in the real situation are also generated. For example, in flight simulators, tilting a chair backward is sometimes used to simulate a forward acceleration. In both the real and simulated cases, the body is pushed into the back of the chair and the gravitoinertial force vector rotates forward in pitch. Subjects may initially perceive the conditions as equivalent, but sooner or later notice that their attitude is incorrect. In amusement park rides like Disney's "Star Tours," noise in the form of chair vibrations, visual or auditory distractions, and rapid transitions to a new state are used to obviate the attitude discrepancies, but the ride still provokes motion sickness even though it lasts only 4:03 min.

In some cases, gravitoinertial VE displays induce a compelling experience of nonterrestrial force conditions for a passive user, but any movements made by the user evoke motion sickness and disorientation. For example, a space vehicle rotating to generate "artificial" gravity might be considered an inertial VE display. Stationary individuals will experience the centripetal force magnitude as body weight and its direction as vertical. Thus, the rotating environment is a successful VE as long as the user remains motionless. However, head movements made during rotation will generate Coriolis accelerations that will alter the vestibular input and sensorimotor control of the head. The head will deviate from the intended movement path and be perceived as moving in still a different way (Lackner & DiZio, 1989b) (see Fig. 1). Coriolis acceleration is among the most powerful nauseogenic stimuli known (cf. Graybiel et al., 1965). The Coriolis force generated will be a function of the head's mass and linear velocity so a HMD would increase the Coriolis force exerted on the head, further alter sensorimotor control of the head, and exacerbate motion sickness symptoms (Lackner & DiZio, 1992). Thus, until adaptation is achieved a rotating environment is not a successful VE when the user moves. We expect that any VE involving linear or angular acceleration produced by passive transport will be subject to this problem: the more compelling the experience of passive whole body movement for the user, the greater will be the sensorimotor disruption resulting from active body movements; adding a mass to the head will exacerbate the problem.

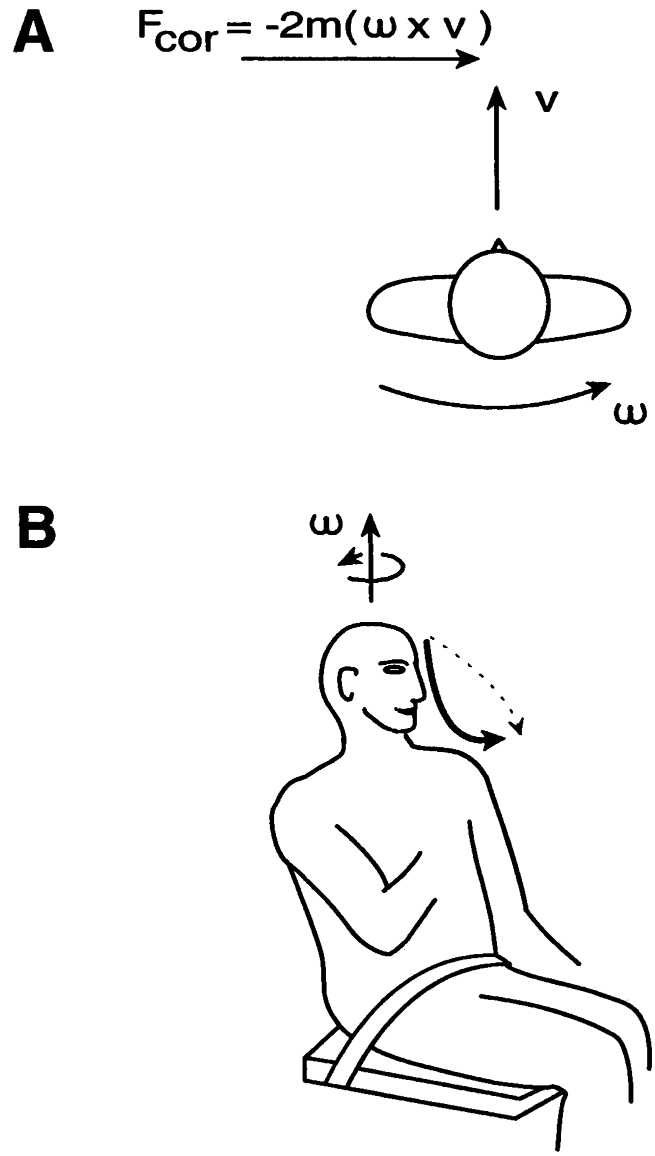


**Figure 1.** *(A) Diagram of relationships among angular velocity of the whole body ($\omega$), linear velocity (v), and mass (m) of the head and Coriolis forces ($F_{cor}$) on the head. (B) Illustration of a subject attempting to tilt the head straight forward (broken arrow) during leftward body rotation ($\omega$). The head deviates to the right (solid arrow) and a complex trajectory is perceived.*

Above, we have indicated that motion sickness may result from either exclusion of the appropriate gravitoinertial VE display or inclusion of an inadequate one. Moreover, in many cases the better a gravitoinertial display is for a passive individual the worse it will be when the individual attempts to move, especially if he or she is bearing a load (such as other VE devices). This does not mean that motion sickness will never be eliminated from VEs involving the experience of either body motion or nonterrestrial force backgrounds. One solution is to endow VE systems with the ability to recognize and manipulate the user's state of adaptation. A full discussion of this is not possible here, but the investigation described below should be illustrative.

### 3.5 An Investigation of Virtual Walking

One's state of adaptation influences the control and perception of natural locomotion. During normal walking, innervation of the neck and torso muscles must be timed and modulated precisely during the step cycle to counteract the tendency for the upper body segments to rotate away from the line of action of the ground reaction force. In everyday life, we take for granted the stability of our body segments relative to one another as well as the stability of the visual world and the support surface as we move about. This is due to our calibration to the viscoinertial properties of our bodies and the terrestrial gravitoinertial force background. We have investigated the sensorimotor and motion sickness responses to walking in an environment in which these relationships are altered (Lackner & DiZio, 1988).

The apparatus used in this experiment was a 1.5-m-diameter circular treadmill with a visual surround that can rotate coaxially. When the floor and visual surround are rotated backward, a subject who is walking in place near the edge of the platform, holding an inertially stationary bar, has the experience of displacing through space in a large radius circle (Bles & Kapteyn, 1977). The floor and surrounding chamber look stationary and the step forces and control of head and torso feel normal. Figure 2A illustrates this arrangement. In fact, a large-radius circular treadmill approximates a linear treadmill, and the gravitoinertial force environment on a linear treadmill moving at constant velocity is the same as in the stationary (on the scale of human locomotion) environment of Earth. In this sense, calibration to a terrestrial environment should allow accurate perception and action without motion sickness in the experimental situation; this is consistent with our findings. However, it should be noted that sitting passively and viewing a rotating visual surround is so nauseogenic that it is often used to provoke symptoms of motion sickness in stationary humans in studies of the physiological responses to motion sickness (Stern et al., 1985).

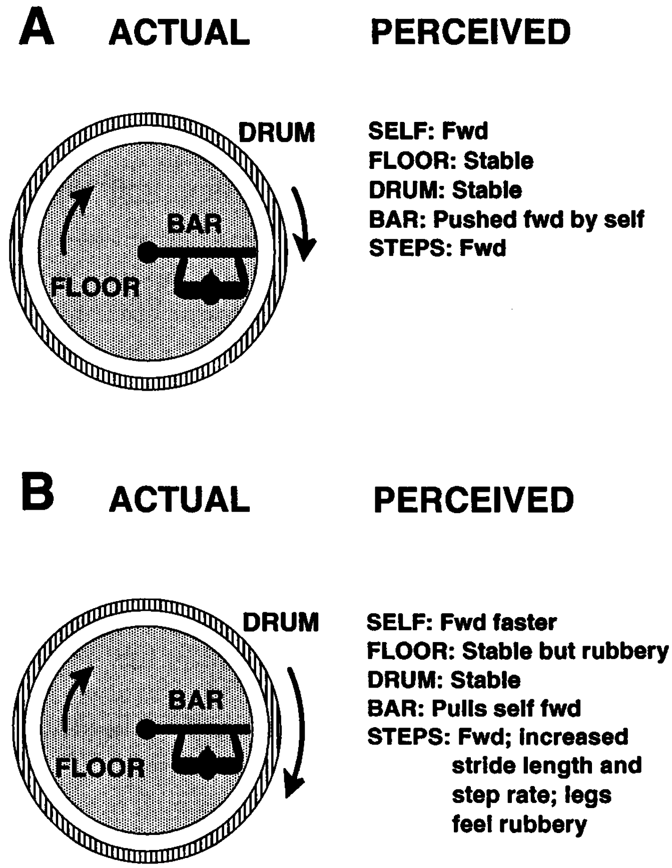


**Figure 2.** *Schematic illustrations of an inertially stationary subject (solid) walking in place on a circular treadmill (shaded) within a moving visual surround (striped). (A) Circular treadmill and visual surround moving at the same velocity. (B) Visual surround moving in the same direction as the circular treadmill but at twice the rate.*

When we change our experimental situation by moving the visual surround backward at twice the rate of the floor, subjects experience themselves to be moving forward more than twice as fast as before. They still perceive the floor and the walls to be stationary and sense no abnormality in the coordination of their body segments. They report that they are moving abnormally fast for the amount of effort they are expending in walking, and perceive two things that are consistent with this. First they report that the bar they are holding has begun to pull them forward and second they perceive a "rubberiness" of their leg and/or the floor such that they are propelled forward at the push-off phase of each step (see Fig. 2B). No motion sickness has been reported during exposures lasting as long as 15 min. The gravitoinertial force environment is normal in the sense described above, but the discrepancy between the motions of the floor and visual surround is highly abnormal. Apparently, our terrestrial calibration includes a constraint that the floor and ground do not move independently, and perceptual remappings occur so that they are represented as stationary when they do move independently. In our case, the remapping involves an attribution of causal motion to the handlebar and a misperception of the rigidity of the legs and/or the floor. It may be that the ability to produce a perceptual interpretation that complies with critical terrestrial constraints and allows well-controlled locomotion is related to the lack of evocation of motion sickness. At any rate it demonstrates the psychological reality of a rearrangement defined at the level of abstractly represented terrestrial constraints rather than at the level of physical dimensions.

During the brief periods when the speed of the walls increases, which would normally be associated with body acceleration, or when the floor and walls both stop, dictating deceleration, subjects cannot control their stepping. They either lurch forward over the bar or find themselves holding onto the bar to keep from falling backward. In contrast to the constant speed conditions, the changing velocity conditions generate rearrangements for which calibration to the terrestrial environment cannot provide an interpretation that allows control of locomotion. Acceleration of the walls generates a constantly changing relationship between floor and walls. Decelerating the floor and surround generates real or virtual gravitoinertial force conditions that do not match those of a normal terrestrial environment. This alters the demands on skeletomuscular control of the head and torso and produces discoordination, revealing the normal calibration of head and torso control to a terrestrial environment. We are about to test whether accelerations and decelerations in the illusion of walking elicit motion sickness; we expect they will.

The above experimental situation alters the demands on head and torso control by altering the relationship between stepping movements and inertial and visual motion. A helmet would further alter these relationships by changing the effective mass of the head. The experimental results imply, by analogy, that the added weight during virtual walking at a constant velocity will not disrupt head–neck control any more than during real walking but may be a disorienting and nauseogenic influence during virtual linear accelerations or turns until adaptation occurs.

### 3.6 Summary

Insofar as motion sickness is associated with conditions requiring recalibration of spatial orientation mechanisms, the analysis of whether a situation will be nauseogenic depends on an adequate understanding of basic mechanisms underlying the control and appreciation of orientation and movement. The situations described above already push our understanding of these mechanisms beyond the limit, and the predictions are tenuous. Accurate observations of the incidence and severity of motion sickness in future VEs may be as important as observations about the fidelity of the experienced environment in improving the theoretical basis for generating better VEs and in understanding mechanisms of human orientation and movement control.

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