7 Perception of Body Motion

Ben D. Lawson and Bernhard E. Riecke

CONTENTS

7.1 INTRODUCTION AND SCOPE

Coordinated locomotion requires matching efferent commands (e.g., to one's limbs) against afferent visual flow information and vestibular and somatosensory (skin, muscle, and joint) signals concerning changing forces on one's body (Guedry, 1992). If accurate afferent information about forces related to one's own movement was suddenly absent during walking, running, carrying, reaching, climbing, etc., one would fall over. Nevertheless, simulation-corroborating acceleration/motion cues are seldom available to users of simulators or virtual environments (VEs) *moving* through a simulated world, a situation that contributes to incoordination, imbalance, cybersickness, and simulator aftereffects. Even VE users riding *passively* in simulated automobiles or aircraft are forced to control the simulated vehicle via visual flow alone, without being able to match visual flow information to the (actual and expected) afferent information about the forces on their own bodies, as they do during real acceleration, deceleration, and turning in vehicles. Consequently, the virtual experience causes unwanted symptoms and fails to be realistic.

This chapter describes the known techniques for eliciting and manipulating perceptions of body acceleration and motion. The focus of discussion is on the user's requirements for perceiving body acceleration, motion, or tilt in a simulator or VE. Understanding how to create virtual acceleration and motion perceptions should improve the training effectiveness and believability of VEs while avoiding unwanted effects (such as motion sickness). This chapter details various methods for exploiting visual, auditory, vestibular, and somatosensory senses (and intermodal sensory interactions) to elicit perceptions of self-motion, self-tilt, or insertion of oneself into an unusual force environment (such as a nonterrestrial planetary body). The authors compare physical acceleration of the user to other (potentially complementary) methods, such as visually induced illusions of self-motion (vection) or somatosensory illusions of self-motion induced by locomotion without displacement (as occurs on some treadmill-based VE). The authors conclude that the most compelling perceptions of body acceleration in VEs will be achieved through mutually enhancing *combinations* of the vestibular, visual, and somatosensory stimuli such as those described in this report.

It is important at the outset for the reader to understand that a *virtual movement* in a VE does not necessarily have to be caused by an illusion of movement in a stationary user. It would be inaccurate to suppose that an acceleration or motion display is only *virtual* when it employs stimuli other than real acceleration to create an illusion of self-motion. By analogy, no one would argue that a visual display is only virtual when it does not stimulate the retina with light. Similarly, the feeling of virtual acceleration or motion refers not to the means by which the acceleration perception is generated, but rather to the resulting perceptual event experienced. Therefore, a successful acceleration/motion simulation will elicit the desired motion perceptions by whatever means best fits the virtual event being portrayed and the overall goals and limitations of the VE designer. The virtual effect desired may be created by generating an illusion of motion where none exists, by really moving the user but in a way that does not correspond exactly to the event being simulated, or by moving the user exactly according to the event being simulated. This last method is a particularly effective approach that employs externally generated acceleration stimuli and self-generated physical motions of the user to match the real acceleration profiles being simulated. This approach involves the use of isomorphic simulations (Grubb, Schmorrow, & Johnson, 2011; Lawson, Sides, & Hickinbotham, 2002), wherein users walk, drive, or fly in a safe and controlled real environment while perceiving themselves to be in a different (e.g., less controlled, more dangerous) VE, such as assisting with a medical evacuation or moving over or through disputed territory. The advantages and limitations of this approach are described and compared to other methods for simulating self-motion. Acceleration simulations that are designed correctly could be used to create more compelling and realistic experiences outside the user's immediate, veridical experience (e.g., training in a simulator building), but appropriate to the VE (e.g., flying in an aircraft).

Our premise is that the purpose of an acceleration simulation is to elicit perceptions of acceleration appropriate to the overall simulation goal by whatever combination of illusory or real motion is most effective. Assuming simulation of a real event is the purpose of a particular VE (which is not always the case), then to be deemed effective that VE should produce no significant adverse side effects unless they are also caused by the real event being simulated. Most importantly, the VE should provide good transfer of skills learned in VE training to performance in the situation being simulated. Provided side effects are appropriate and transfer of training is satisfactory, it would also be advantageous for the VE to elicit consistent and controllable acceleration perceptions that are difficult to distinguish from the real event being simulated.

Normal movement control relies on more senses than are typically stimulated by a VE. The perception of real body acceleration, motion, and orientation involves vision, audition, vestibular sensation, and somesthesia* (which refers to detection by tactile and kinesthetic somatosensory systems, including cutaneous, muscle, and joint receptors). Similarly, during simulated activities, the aforementioned sensory modalities can be exploited to elicit the perception of acceleration. For example, the motion of large visual fields around the user is known to act upon the vestibular nucleus (and associated structures) and thereby to induce a compelling illusion of self-motion (Dichgans & Brandt, 1978). A visually induced illusion of self-motion is commonly referred to as vection, a term attributed to Tschermak (1931). Vection can be considered an acceleration perception that indirectly implicates vestibular involvement. The use of vection as a means for simulating self-motion in a VE is treated in Section 7.2.1 and in Chapter 18 of this book (Hettinger, Schmidt, Jones, & Keshavarz, 2014).

Just as visual stimuli can provide acceleration/motion cues, so can somatosensory stimuli. For example, some evidence suggests that walking in place on a substrate that moves can be exploited to enhance the perception of naturalistic locomotion through a VE and can induce compensatory eye movements not unlike those elicited by real body motion (Bles, 1979; Brandt, Büchele, & Arnold, 1977; DiZio & Lackner, 2002; Lackner & DiZio, 1988). Like visual vection, walking in place can be considered an acceleration simulation if it leads the user to perceive self-acceleration or self-motion (Section 7.2.3.2; also Appendix A of Hollerbach, 2002; Lawson et al., 2002; Steinicke, Vissell, Campos, & Lecuyer, 2013).

Visual and somatosensory cues are considered in this chapter, but emphasis is placed on the vestibular modality. Since the vestibular organs are specifically designed to sense acceleration, a rudimentary understanding of human vestibular function is necessary in order to employ physical acceleration effectively as part of a VE. This chapter provides an introduction to the *vestibular channel* of the VE stimulus and details different methods for exploiting knowledge about the vestibular modality and cross-modal interactions to elicit perceptions of self-motion, self-tilt, and insertion of oneself into an unusual force environment (such as a nonterrestrial planetary body). These effects can be achieved by the use of moving simulators, centrifuges, and other acceleration

* The authors avoid the terms *proprioceptive* or *haptic* when referring collectively to skin, muscle, and joint senses, because *proprioception* includes the vestibular modality, while *haptic* refers to active manual exploration of the world via both cutaneous and kinesthetic senses.

devices (Stanney & Cohn, 2006) or by isomorphic real locomotion (Lawson et al., 2002). All of these *real-motion* methods tend to directly stimulate the vestibular organs. The vestibular modality should be exploited by VE designers to induce feelings of acceleration when they are desirable and to avoid feelings of acceleration when they are undesirable, yet are required because of the logistic constraints of the simulator and the space within which it operates. For example, moving-base simulators often employ a subthreshold motion during relatively quiescent periods in the simulation. This is done to slowly reposition the user and ready the motion platform to achieve the desired acceleration profile the next time a strong acceleration perception is required as part of the simulation. In discussing the vestibular channel in VEs, the essential qualities of the stimulus (acceleration) and the receptor (the vestibular end organ) will be briefly introduced. The authors will introduce ways in which the vestibular, visual, and somatosensory systems (and some of their cross-modal interactions) can be exploited to create, prevent, or modify acceleration/motion perceptions. We first discuss the general approaches for eliciting motion percepts without physical acceleration and then address the approaches that require physical acceleration. Finally, we detail specific ways in which knowledge concerning the vestibular system can be exploited systematically to induce perceptions of body tilt, rotation, translation, absence of tilt, absence of rotation, absence of translation, and changes in the magnitude of gravity.

7.2 ELICITING ACCELERATION/MOTION PERCEPTIONS WITHOUT PHYSICAL ACCELERATION OF THE USER

Physical motion of the user is the most effective and straightforward way to elicit perceptions of acceleration and self-motion. Unfortunately, this approach often requires significant time and money to implement. Large-scale moving-base simulators can cost millions of dollars and require considerable expertise, space, and safety precautions. Even seemingly simple free-space walking areas (Section 7.5.3) can pose considerable challenges due to the need to provide (1) low-latency and accurate tracking across the entire motion envelope (Foxlin, 2002), (2) high-quality naturalistic visuals spanning a large field of view (FOV), and (3) measures to ensure that users do not stray beyond the safe boundaries of the walking area (Sections 7.5.3 and 7.5.5). Thus, different options have been explored for eliciting illusory acceleration/motion perceptions without the need for physical acceleration of the user.

In this section, we will discuss how different stimuli and procedures can be used to cause VE users to experience sensations of self-motion and consider how these can and be combined with other corroborating cues to yield maximum benefit. For recent reviews of the relevance of self-motion illusions to VE, see Chapter 18 (Hettinger, Schmidt, Jones, & Keshavarz, 2014) and also Palmisano, Allison, Kim, and Bonato (2011); Riecke (2009, 2011); Riecke and Schulte-Pelkum (2013); and Väljamäe (2009). Excellent older reviews on visually induced vection are provided by Andersen (1986), Dichgans and Brandt (1978), Howard (1986a), Mergner and Becker (1990), and Warren and Wertheim (1990). The known methods for inducing illusions of self-motion are discussed in the following text.

7.2.1 VISUALLY INDUCED ILLUSIONS OF SELF-MOTION

Self-motion and displacement sensations can be elicited via tilting the frame of reference, moving a visual frame of reference relative to the observer, or the aftereffects of prolonged movement of a visual frame of reference, such as an *optokinetic drum* surrounding an observer (Dichgans & Brandt, 1978). These are promising methods if applied with a full knowledge of the psychophysics of human perception and the factors that give rise to visually induced discomfort (Lawson et al., 2002). Vection can be elicited by nonvisual stimuli, but visual cues have received the most attention in vection research to date, and the first accounts of how large-field visual motion can induce illusory embodied self-motion date back more than a century ago (Helmholtz, 1866; Mach, 1875;

Urbantschitsch, 1897; Warren, 1895; Wood, 1895). Many readers are familiar with the illusion described by Helmholtz (1866), wherein one can experience the illusion that one's train is starting to move when instead the train on the adjacent track has started to move.

Such self-motion illusions can be elicited for translations and rotations and have been termed linear and circular vection, respectively (Berthoz, Pavard, & Young, 1975; Fischer & Kornmüller, 1930; Tschermak, 1931). Adverse symptoms of motion sickness may occur, with at least 20% of people reporting stomach symptoms during prolonged exposure to a provocative optokinetic stimulus (Lawson, 2014, Chapter 23). Roll and pitch rotations of the visual field may be more disturbing than yaw rotations (Bles, Bos, Graaf, Groen, & Wertheim, 1998), since a visual illusion of body motion or position that does not match the actual upright position of a seated person creates a *sensory conflict* between visual and proprioceptive (vestibular and somatosensory) cues (Reason & Brand, 1975). Roll or pitch optokinetics stimuli also can elicit paradoxical illusions of continued body rotation despite a limited sensation of body tilt not usually exceeding approximately 20° (Allison, Howard, & Zacher, 1999; Held, Dichgans, & Bauer, 1975; Young, Oman, & Dichgans, 1975).

For many simulations, it is essential to ensure low incidence and severity of adverse symptoms such as simulator sickness, which sometimes correlates positively with vection, as discussed in Chapter 26 (Keshavarz, Hecht, & Lawson, 2014), Chapter 18 (Hettinger, Schmidt, Jones, & Keshavarz, 2014), and elsewhere (Hettinger, Berbaum, Kennedy, Dunlap, & Nolan, 1990; Kennedy et al., 2003; Lawson, 2005; Palmisano, Bonato, Bubka, & Folder, 2007). The causal relation between vection and sickness is a subject of debate and the evidence is mixed. For example, it has been observed that simulator sickness increases for larger visual–vestibular cue conflicts, whereas vection is enhanced by reduced cue conflicts (Kennedy et al., 2003; Palmisano et al., 2007). A number of other factors have been found to facilitate and strengthen visually induced vection, as detailed by Andersen (1986), Dichgans and Brandt (1978), Howard (1986a), Mergner and Becker (1990), Riecke (2011), Riecke and Schulte-Pelkum (2013), and Warren and Wertheim, 1990). In the following section, we will discuss some of these factors.

Increasing the FOV covered by the moving visual stimulus generally enhances vection to a point where full-field stimulation can yield sensations of self-motion that are difficult to distinguish from actual self-motion (Berthoz et al., 1975; Brandt, Dichgans, & Koenig, 1973; Dichgans & Brandt, 1978; Held et al., 1975; Lawson, 2005). However, small fields can induce vection also when they are radially expanding (Andersen & Braunstein, 1985).

Higher stimulus velocity (but not necessarily higher acceleration to reach that constant dwell velocity) generally enhances vection, up to 120°/s for circular yaw vection (Allison et al., 1999; Brandt et al., 1973; Dichgans & Brandt, 1978; Howard, 1986a). Furthermore, vection can be enhanced by increasing the amount of optical texture (Brandt, Wist, & Dichgans, 1975; Dichgans & Brandt, 1978). For applications where there is little optic flow (e.g., flight or space travel simulations where there are few nearby objects), this could be a challenge, and one may need to carefully add ecologically valid visual elements to provide sufficient optic flow. For example, it may be necessary to add a few clouds to a flight simulation.

Forward linear vection can also be facilitated by adding moderate simulated camera shake (*viewpoint jitter*) to the simulations (Palmisano et al., 2011; Palmisano, Gillam, & Blackburn, 2000). This finding from basic research could be employed in motion simulations by carefully adding (instead of filtering out or ignoring) some naturally occurring viewpoint jitter, for example, from bouncing head motions during walking (Ash, Palmisano, Apthorp, & Allison, 2013; Bubka & Bonato, 2010) or vehicle shaking due to motor vibrations or rough roads.

Illusory self-motion may arise instantaneously but usually requires several seconds. When 45 experiment participants were each completely immersed in a slowly turning optokinetic sphere (Lawson, 2005), 16 reported vection within 3 s of opening their eyes. Therefore, under optimal conditions, only about 36% of simulator/VE users would be expected to get vection without an appreciable delay. In fact, 14 s was the average delay in Lawson. A key challenge when attempting to employ self-motion illusions to enhance VEs is the need to reduce the onset latency to an acceptable value. To this end, it can be useful to consider not only *bottom-up*, visual stimulus parameters but also intermodal facilitations (Section 7.6; Riecke & Schulte-Pelkum, 2013) and higher-level/cognitive or *top-down* factors (Section 7.8; also Riecke, 2009, 2011; Riecke & Schulte-Pelkum, 2013; Riecke, Västfjäll, Larsson, & Schulte-Pelkum, 2005; Seno, Ito, & Sunaga, 2009; and Väljamäe 2009).

7.2.2 Auditory Illusions of Self-Motion

Self-motion sensations can be elicited via motion of auditory surrounds and the aftereffects thereof (Lackner, 1977). Blindfolded listeners can perceive *audiokinetic* illusions of self-motion from moving sound fields (Dodge, 1923; Lackner, 1977; Marme-Karelse & Bles, 1977). While visually induced vection can be induced in all users and can yield strong self-motion illusions that may be indistinguishable from physical self-motion, auditory vection tends to be weaker and more variable. Auditory vection occurs in 20%–75% of blindfolded listeners, depending on various stimulus factors (Väljamäe, 2009). For example, Larsson, Västfjäll, and Kleiner (2004) reported circular vection in 23%–50% of blindfolded listeners when single sound sources were simulated and 28%–66% when multiple sound sources were simulated (depending on the type of sounds used). Adding moving sound fields has been shown to enhance both visually induced vection (Riecke, Schulte-Pelkum, Caniard, & Bülthoff, 2005; Riecke, Väljamäe, & Schulte-Pelkum, 2009) and kinesthetic vection elicited by stepping along a rotating floor platter or *circular treadmill* (Riecke, Feuereissen, Rieser, & McNamara, 2011). Thus, moving auditory cues can support and enhance self-motion illusions. Given the relative ease and affordability with which high-fidelity sound can be simulated, adding spatialized sound should be considered, since it is likely to increase the overall realism of a simulation and also facilitate perceived self-motion through a VE.

7.2.3 Somatosensory Illusions of Self-Motion

7.2.3.1 Tactile Illusions due to Contact with a Moving Frame of Reference

Acceleration perceptions can be elicited via moving touch and pressure cues and the aftereffects thereof (DiZio & Lackner, 2002; see also Brandt et al., 1977; Lackner & DiZio, 1984; Lackner & Graybiel, 1977). This is a promising method, especially when used in conjunction with confirmatory information from other sensory modalities. Relatively little is known about this approach to creating VE, compared to visual or auditory methods.

7.2.3.2 Kinesthetic Illusions due to Limb Movement

The literature concerning kinesthetic illusions due to limb movement is complex and the findings vary with the experimental situation. Self-motion perceptions can be elicited by voluntary kinesthetic behaviors such as locomotion without displacement (walking in place), stationary pedaling, or moving one's arm with a rotating surround (as well as the aftereffects of these behaviors) (Brandt et al., 1977; Dizio & Lackner, 2002; Hollerbach, 2002; Lackner & DiZio, 1988, 1993). For example, when people sit stationary inside a slowly rotating optokinetic drum in complete darkness, they may perceive compelling illusory self-rotation (*arthrokinetic circular vection*) when they touch the rotating surrounding cylinder and follow its motion with one hand such that their arm moves about the shoulder joint (Brandt et al., 1977). Although this condition was called *passive*, it was accomplished by reaching out with an unsupported arm and maintaining voluntary contact with the drum as it turned under its own power. Under these conditions, circular vection occurs within 1–3 s and is reportedly indistinguishable from actual self-motion. Arthrokinetic nystagmus and aftereffects for nystagmus and circular vection were observed as well. Similar to kinesthetic circular vection caused by walking in place, illusory self-rotation is in the direction opposite of the rotating cylinder (Bles, 1981; Bles & Kapteyn, 1977; Brandt et al., 1977).

For stimulus rotations greater than 10°/s, Brandt et al.'s participants performed the same voluntary unsupported reaching out and following of the drum's motion but used both arms and placed them alternately on the inner side of the rotating cylinder, similar to a walking motion. Contrary to what has been implied by a few secondary literature sources, this multiarm hand-walking motion did not cause appreciable arthrokinetic vection or nystagmus (albeit no descriptive or inferential statistics were provided). This differs from circular treadmill walking, where stepping along in time with a moving platform elicits vection (Bles, 1981; Bles & Kapteyn, 1977; Riecke et al., 2011). Actively stepping to push the platform backward with both feet alternately also seems to elicit vection (anecdotal observations by Riecke).

A few observations may partially explain the different findings for two-hand walking versus two-foot stepping around: (1) Human locomotion is usually performed with the legs, whose rhythmic motion has a close association with human movement through the world (albeit not by stepping in a circle while seated); (2) The ground surface beneath one's feet provides a strong frame of reference that is usually stationary during locomotion; (3) In the aforementioned studies of seated stepping, the legs moved through a smaller arc than the arc the two arms traversed in Brandt et al., so greater rhythmic limb alternation would occur during stepping, which would corroborate the perception of body locomotion. We recommend the evaluation of these factors in future studies.

Bles and colleagues demonstrated that arthrokinetic vection can occur for linear sideways motion, although only in about 37% of trials (Bles, Jelmorini, Bekkering, & de Graaf, 1995). Blindfolded, seated participants were asked to use hand-walking motions to stay in contact with a flat table-like surface that moved at constant (0.1 m/s^2) acceleration in the frontoparallel plane (left/right). While these findings are promising, there has been little attempt to exploit them for motion simulation in a VE. This may be because of the lack of naturalness of this method and the fact that the hands must be free to carry out tasks. Nevertheless, this could be a useful adjunct to simulations of crawling or climbing in a VE.

While it is not clear how well treadmill walking works for eliciting vection, there is clear evidence that stepping in place along a rotating floor platter can induce or contribute to circular vection (if users walk in place or step around near the center of the rotating floor) or curvilinear vection (if users walk off-center) in the direction opposite of the floor motion (Bles, 1981; Bles & Kapteyn, 1977; Bruggeman, Piuneu, Rieser, & Pick, 2009; Lackner & DiZio, 1988; Riecke et al., 2011). Such apparent stepping around can provide compelling self-motion illusions and is even accompanied by nystagmus and Coriolis-like (pseudo-Coriolis or pseudo-Purkinje) effects when participants perform active head tilts (Bles, 1981; Bles & Kapteyn, 1977).

Feeling like one is actually walking forward through a VE may enhance realism and presence. Given the increasing availability and affordability of linear treadmills, they are becoming more common in VE applications. They allow for fairly natural locomotion, at least in the forward direction (Steinicke et al., 2013). The biomechanics and coordination of walking on a treadmill are more similar to natural walking than walking in place on a stationary floor (another approach that has been used in VEs), especially in advanced treadmills that use force-feedback harnesses (Hollberbach, 2002; Steinicke et al., 2013). Nevertheless, somatosensory cues from walking on even advanced linear treadmills are not identical to real walking, which requires more backward-directed force against the substrate to maintain forward locomotion and requires different forces to start, stop, and turn compared to a treadmill. It is not clear whether linear forward walking on a treadmill is sufficient to elicit a compelling sensation of self-motion. For example, Durgin et al. (2005) pointed out that "during treadmill locomotion, there is rarely any illusion that one is actually moving forward" (p. 401).

Unfortunately, adding velocity-matched treadmill walking to a visual motion simulation does not always enhance self-motion perception (Onimaru, Sato, & Kitazaki, 2010; Seno, Ito, & Sunaga, 2011; but see Lackner & Dizio, 1988). It can sometimes impair self-motion perception, even though it is designed to correspond to our natural (eyes-open) walking experience (Ash et al., 2013; Kitazaki, Onimaru, & Sato, 2010; Onimaru et al., 2010; see also discussion in Riecke & Schulte-Pelkum, 2013). It is possible that the additional head motions associated with walking decrease visual vection (Lackner & Teixiera, 1977; Teixeira & Lackner, 1979; Viirre, Sessoms, & Gotshall, 2012). It is also possible that visual and tactile/kinesthetic cues for self-motion must be very closely matched to be interpreted as synergistic rather than conflicting. However, the pattern of findings is complicated, because Lackner and DiZio (1988) did not observe walking on a circular treadmill to weaken concordant visual vection, although interpretations of body motion were reported, which *captured* visual vection in favor of the kinesthetic cues when the two were put in opposition. Further research is needed to better understand the interactions between visual and tactile/kinesthetic walking cues during circular apparent stepping around and linear treadmill walking. Until then, it seems advisable to carefully evaluate VE walking applications to ensure that the cues from walking provide the intended benefit. A more extensive discussion of walking in VE can be found in Steinicke et al. (2013). It is already clear that rotational, but not necessarily translational, self-motion can be elicited merely by walking in place in the dark. Moreover, recent evidence shows that walking motions on a circular treadmill can enhance visually induced circular vection (Freiberg et al., 2013).

7.2.3.3 Kinesthetic Illusions due to Vibration of Localized Body Regions

Self-motion perceptions can be elicited by vibration of localized body regions. Vibration of skeletal muscles and tendons involved in human postural coordination can elicit a variety of self-motion perceptions (Lackner, 1988; Lackner & Levine, 1979; Levine & Lackner, 1979), most likely because the vibration-induced activity in the muscle spindles is interpreted by the central nervous system as muscle lengthening associated with movement around a body joint. For example, vibration of the Achilles tendons of a standing, restrained observer can trigger an illusion of forward pitch about an ankle-centered axis. Skeletal muscle vibration can elicit apparent motion perceptions of many different types but will not be employed as a primary method of inducing motion perceptions in VE because it requires dark or near-dark conditions as well as precise placement and pressure of the vibrator and appropriate restraint of the limb to achieve an optimal effect. Nevertheless, the technique is inexpensive to implement and should be explored further to determine whether it can strengthen illusions of self-motion elicited by other means.

7.2.4 Methods for Eliciting Vestibular Illusions without Accelerating the User

7.2.4.1 Caloric Stimulation

Caloric stimulation of the ear canal via irrigation with ice water (National Research Council, 1992) causes a change in temperature on one side of the semicircular canal, which triggers convection currents that can elicit a sensation of turning. This is an effective method that can be applied unilaterally, but it is somewhat invasive and quite unpleasant, and the specific motion perception is difficult to alter from moment to moment.

7.2.4.2 Galvanic Vestibular Stimulation

Electrical stimulation of the vestibular nerve fibers is an effective way to elicit movement sensations and balance reflexes (St. George & Fitzpatrick, 2011), but when done invasively (as in the animal model), it is not a promising method for general (nonprosthetic) use in humans. Fortunately, low-intensity galvanic vestibular stimulation (GVS) can be achieved by placing electrodes in the mastoid region just behind the ear, and this may be a method for achieving somewhat controlled velocity perceptions in normal humans (Lenggenhager, Lopez, & Blanke, 2008; Etard, Normand, Pottier, & Denise, 1998). At a neural level, applying a small current bilaterally to the mastoids modulates vestibular firing rates, decreasing them on the anodal side and increasing them on the cathodal side. This presumably is caused by GVS conveying a signal of head motion toward the cathodal side of stimulation (in the absence of an efferent command to move the head), which in turn leads to an automatic adjustment response toward the anodal side (St. George & Fitzpatrick, 2011; Wardman & Fitzpatrick, 2002; Wardman, Taylor, & Fitzpatrick, 2003). This GVS method does not place electrodes inside the skull, but it uses currents that are salient and can be disturbing. Fortunately, even low currents of GVS can be used to affect gait, presumably by altering the perception of self-motion (Bent, McFadyen, French Merkley, Kennedy, & Inglis, 2000). GVS also can modulate the strength of visually induced self-motion illusions (Maeda, Ando, & Sugimoto, 2005) and affect the perceived trajectory of visually induced illusory self-motion (Lepecq et al., 2006).

GVS has wider applications beyond the simple elicitation of a self-motion illusion. GVS can systematically alter the perceived path during active walking and passive wheelchair transport (being pushed by an experimenter; Fitzpatrick, Wardman, & Taylor, 1999). Similarly, GVS can be used to modify the walking direction of blindfolded participants, who will tend to turn toward the side on which the anodal electrode was placed (Fitzpatrick et al., 1999). While dynamically adjusting GVS can be used to *remotely control* blindfolded users' walking trajectories, the effectiveness of this approach depends on one's head orientation with respect to gravity and is maximal when the head is tilted forward by 72° (St. George & Fitzpatrick, 2011). Raising one's head to be upright results in sideways stumbling to regain balance, but no further orientation responses due to GVS. This limits this potential VE application of GVS to situations where head orientation is either fixed or can be dynamically monitored and kept within a useful range.

Responses are fairly predictable for different head orientations. When the head is slightly tilted backward, GVS will induce sideways (lateral) sway toward the anode in standing humans (St. George & Fitzpatrick, 2011). Correspondingly, GVS will yield sagittal (forward/backward) sway when one's head is tilted 90° to the left or right. Finally, sensations of horizontal rotation (but no sway) can be induced by GVS when one's head is tilted forward (by 72°).

7.2.4.3 Drug Effects

Dysfunctions in a given vestibular labyrinth or imbalances in the normal interaction of the respective labyrinths (such as may result from inner ear infections, Ménière's syndrome, or ototoxic drug treatments) can create feelings of movement. It would be unethical to intentionally produce such invasive effects by similar means because of the long-term adverse effects. The vestibular effects of certain drugs such as alcohol (Fetter, Haslwanter, Bork, & Dichgans, 1999) are reversible, but not pleasant or easily controllable. Moreover, such drugs produce unpleasant side effects and raise safety concerns. Overall, current drugs are not a promising approach for eliciting illusions of self-motion.

7.2.4.4 Low-Frequency Sound Effects

Low-frequency (e.g., below 20 Hz) acoustic vibrations of high intensity are not necessarily audible but may act upon the vestibular organs of healthy people (Parker, Tubbs, Ritz, & Wood, 1976) and people with vestibular pathologies (Minor, Solomon, Zinreich, & Zee, 1998), eliciting vertigo. This is currently not a promising method for eliciting acceleration perceptions because loud sounds (125 dB and above; Parker et al., 1976) are required to get only a portion of users vertiginous, because unpleasant symptoms can result, and because long-term consequences to auditory and vestibular organs could be adverse (Lawson & Rupert, 2010).

7.2.4.5 Other *Vestibular* Effects Not Requiring Body Acceleration

Eliciting vertigo via looking over a visual cliff (Brandt, 1999), via postural hypotension (Baloh & Honrubia, 1979), or via atmospheric pressure changes (Benson, 1988) is effective for producing nonspecific feelings of instability, dizziness, or falling but is not conducive to controllable motion perceptions and would give rise to safety concerns for certain individuals. The vestibular or visual–vestibular systems play a role in these effects.

7.3 ELICITING ACCELERATION OR MOTION PERCEPTIONS

The various methods for creating the perception of displacement, tilt, velocity, acceleration, or abnormal G-force upon one's body are enumerated briefly in this section. Not all of these methods are practical, nor do all of them involve imposing real accelerations on the user. Nevertheless, the most obvious way to elicit the perception of dynamic body movement through a VE is by real physical motion of the user that is perceived as such. Physical motion can be achieved passively with moving devices such as moving-base simulators, centrifuges, and real vehicles. Physical motion also can be achieved by allowing the user to move physically through a real environment that serves as an ambient context for the VE. Allowing for real user motion is a very effective and controllable way to create acceleration perceptions in a VE, provided the VE customer can afford it and the simulations are designed by specialists who understand simulators, the psychophysics of human acceleration sensations, and the factors that give rise to motion-induced discomfort.

7.3.1 Changing Perceived Body Weight Using Real Acceleration Stimuli

Physical acceleration of the user is not always perceived as such. Acceleration that is prolonged (e.g., aboard a centrifuge) can lead to the perception of altered body weight instead. Perceived addition or subtraction of body weight during movement through space can be used to enhance the simulation of high-performance vehicles or nonterrestrial environments (Guedry, 1974; Guedry, Richard, Hixson, & Niven, 1973; Lackner & Graybiel, 1980). It is important for the reader to realize that acceleration perceptions one can elicit in a VE are not limited to feelings of movement through space. Since gravity is one type of acceleration (according to Einstein's stated equivalence of inertial and gravitational force; see de Broglie, 1951), the perception of unusual G-forces on one's body qualifies as an acceleration perception also.

It is also possible to cause a temporary illusion of changed body weight (or at least the amount of effort required to move the body) via a simple trampoline. Prolonged jumping on a trampoline causes an altered sensation of effort required to jump (partly because one feels *too heavy*) immediately afterward (Marquez et al., 2010). This is presumably due to a rapid recalibration of the meaning of vestibular and somatosensory in reference to one's own motor commands, similar to that which occurs during knee bends performed during the high-G phases of parabolic flight (Lackner, 1992).

7.3.2 Illusions of Self-Motion Associated with a Change of Velocity

Changing the motion velocity or coming to a complete halt can induce compelling self-motion illusions and motion aftereffects, especially when no visual or other cues are available to disambiguate the situation (Guedry, 1974). For example, when being rotated on center in the earth-vertical z-axis at constant velocity in darkness, vestibular signals from the horizontal semicircular canals will fade over time. When this constant-velocity rotation is suddenly stopped, one can perceive a strong (illusory) rotation in the direction opposite of the original motion, despite being physically stationary. This is a useful adjunct to other methods, especially when combined with confirmatory information from other sensory modalities. For example, a rotation aftereffect indicating that one is turning to the right can be used to hasten and strengthen a desired visual vection illusion of turning to the right, as is frequently done in a military acceleration device used for ground-based disorientation training (Guedry, 1980).

7.3.3 Illusions of Self-Motion Associated with Multiaxis Rotation

Self-rotation perceptions can be produced by prolonged constant-velocity rotation in one axis followed by a head movement in another, nonparallel axis (Guedry & Benson, 1978). Under certain circumstances (e.g., after prolonged constant-velocity rotation without good visual references concerning the outside world), this stimulus elicits the perception of angular head velocity in a third axis orthogonal to the axis of the body rotation and the head rotation. This is a useful approach only when the resulting Coriolis cross-coupling stimulus is relatively mild or the user is resistant to motion sickness. Pronounced discomfort can arise among susceptible individuals making repeated, large, or rapid head movements after prolonged body rotation, especially when body rotation occurs at high velocity. However, veridical earth-referenced cues concerning one's true motion can lessen the unpleasant effects (Lawson, Guedry, Rupert, & Anderson, 1994; Lawson, Rupert, Guedry, Grissett, & Mead, 1997). Unfortunately, these helpful cues are likely to reduce the perceptual effects of illusory rotation as well. Therefore, they are mostly useful for diminishing sickening effects when passive or voluntary head movement must be performed to accomplish other (e.g., training-related) purposes of the simulation.

7.3.4 Illusions Associated with Static or Dynamic Body Tilt

Alterations in perceived orientation can be induced via static body tilt and the aftereffects thereof. In this case, the acceleration stimulus is provided by gravity. This is a useful adjunct to other methods in this section, but simple body tilt by itself elicits illusory effects that are mainly restricted to the perception of the orientation of visual targets. Dynamic body tilt is, however, frequently used in moving-base motion simulations, for example, when users are tilted backward and thus pressed against their seat to simulate physical forward accelerations that cannot be veridically performed due to the limited motion envelope of most platforms. Since otoliths by themselves may not readily distinguish between inertial (acceleration) and gravitational forces, the human system readily uses information from other sensory modalities to disambiguate gravitoinertial forces, a process that can be modeled by Bayesian sensor fusion (MacNeilage, Banks, Berger, & Bülthoff, 2007). This can be used to widen the coherence zone in which cross-sensory conflict remains unnoticed or at least has little detrimental impact (Steen, 1998) and can help to mask imperfections in motion cueing and motion washout filtering in moving-base simulators.

7.3.5 Whole-Body Vibration Effects

Subtle vibrations of the participants' seat may not by themselves be able to reliably induce sensations of self-motion, but they have been found to facilitate visual (Riecke et al., 2005; Schulte-Pelkum, 2007) and auditory vection (Riecke, Feuereissen, & Rieser, 2009; Riecke et al., 2005; Väljamäe, Larsson, Västfjäll, & Kleiner, 2006), which are discussed in the following texts. Since typical vibrations (and to some degree, special infrasound vibrations) can be applied in motion simulations relatively cheaply and easily, they should be added whenever feasible to enhance the overall realism of the simulation. This should be done with an awareness of the effects arising from localized head vibration, per se (Lackner & Graybiel, 1974).

7.4 SPECIFIC CATEGORIES OF ACCELERATION/MOTION PERCEPTIONS INVOLVING ACCELERATION STIMULI TO THE VESTIBULAR MODALITY

To understand how best to elicit the desired perceptions in a simulator or VE, one should start with a basic knowledge of how perceptions are formed in the natural world. To understand how perceptions are formed, one must begin with the stimulus, that is, the qualities in the physical world that are detected by the sensory system of interest. If one wishes to meet the user's *visual requirements* with a display, one manipulates the intensity and wavelength of the light reaching the user's eye so as to match the stimuli that would be received if the viewer were physically present inside the virtual world. Similarly, the amplitude and frequency of vibration of air molecules are sensed by the auditory modality and then perceived by the listener as loudness and pitch. Air vibrations of sufficient magnitude can be sensed by other sensory modalities as well, but the auditory modality is specifically designed to detect them. In the case of motion perception, the usual stimulus is acceleration (or more properly the forces to the body resulting from acceleration), which is sensed or inferred by multiple sensory systems, among which the vestibular system is specifically designed with this as its primary purpose. Therefore, if one wishes to meet the users' *vestibular requirements*, one either manipulates the acceleration stimulus directly or finds some other way to stimulate the vestibular system in a way comparable to acceleration.

In any VE, certain system requirements must be met to generate an appropriate stimulus, while critical user requirements dictated by the functional properties of the user's perceptual apparatus must be met for the VE to be compelling and effective. Manipulating the quality of the stimulus itself is only one aspect of a good simulation. It is equally important to understand the functioning and limitations of the sensory modalities one is stimulating to evoke a synthetic experience effectively. Sometimes it may not be possible or desirable in a VE to recreate the stimuli the users would receive if they were in the real world (e.g., harmful forces to the body). In cases where it is desirable but does not appear possible, a solution might be finessed by exploiting known principles of sensory functioning.

Introductory information concerning the functioning of the vestibular system is presented in this section. Such information can be exploited to enhance feelings of acceleration, force, and self-motion. The human vestibular modality is evolved to detect accelerations; it can do so in the absence of visual or somatosensory cues, but these cues are present most of the time during self-generated movements in the natural world. The sensory qualities to which the vestibular modality is sensitive include linear and angular accelerations due to self-motion and gravity. Linear and angular accelerations are detected by the otolith organs and the semicircular canals, respectively. These organs are described briefly as follows. (For detailed review, see the recommended readings at the end of this chapter.)

The otolith organs of the inner ear detect linear accelerations of the head; they also sense angular motion that produces changes in the angle of the perceiver's body relative to the earth's gravity vector. The otolith organs detect changes in the magnitude and direction of linear gravitoinertial force vectors via hair cell mechanoreceptors, which are embedded in gelatinous membranes containing tiny crystals of calcium carbonate called otoconia. The otoconia are more dense than the surrounding medium and hence lag behind motions of the head very slightly due to their inertia, causing a corresponding deformation of the hair cells.

Three semicircular canals located in each inner ear code angular motion in three roughly orthogonal axes. The semicircular canals are fluid-filled rings with a gelatinous structure called the cupula obstructing each ring. The gelatinous cupula is embedded with hair cells that are deformed when the cupula is itself deformed by very small changes in fluid pressure caused by angular acceleration of the semicircular canals. This slight deformation of the cupula is caused by the inertia of the fluid in the canal, which wants to remain at rest when the head is turned.

Collectively, the semicircular canals and otolith organs make up the equilibrium organs of the nonauditory portion of the human labyrinth. The semicircular canals and otolith organs interact with one another (and with other sensory modalities) during the processing of complex stimuli involving simultaneous angular and linear acceleration. The mutual interaction of otoliths and canals provides one explanation for why the perception of self-tilt during off-center rotation (i.e., rotation around a central axis that is located at some radial distance from one's body, as occurs on a merry-go-round) initially lags behind the stimulus given by the rate of change in the direction of the resultant gravitoinertial force vector (Graybiel & Brown, 1950; Lawson, Mead, Chapman, & Guedry, 1996). This lag effect is often attributed to suppression of the otolith system by the angular acceleration signal being processed and transmitted by the semicircular canals (Lawson et al., 1996). Numerous other intralabyrinthine interactions can be identified (Guedry & Benson, 1978; Reason & Brand, 1975) as well as important interactions among the labyrinthine and nonlabyrinthine sensory modalities, including vision (Dichgans & Brandt, 1978), audition (Lackner, 1977), and somesthesia (Bles, 1979; Lackner & Graybiel, 1978). Finally, purely otolithic mechanisms for distinguishing tilt from translation have been proposed (Wood, 2002).

The vestibular system is involved in several aspects of human functioning besides the perception of acceleration, including the reflexive control of gaze stabilization (to maintain clear vision during head movement), head righting, postural equilibrium, coordinated locomotion, certain reaching behaviors, and even wayfinding (Goldberg et al., 2011). Functioning vestibular organs are probably critical to the elicitation of unpleasant symptoms such as motion sickness induced by real or apparent motion (Cheung, Howard, & Money, 1991). A comprehensive explanation of vestibular function, neurovestibular pathways, or the psychophysics of vestibular perception is not necessary for the reader to gain a rudimentary grasp of the practical options available for eliciting acceleration perceptions in VEs. (The Appendix for this chapter provides a list of recommended readings for those who wish to learn more about vestibular function and psychophysics.) The most practical options available for eliciting acceleration perceptions are evaluated in the following text.

The vestibular end organs are stimulated directly by many of the methods of eliciting acceleration/motion perceptions covered in Section 7.3, including physical tilt or motion of the user, rotation aftereffects, caloric stimulation, certain acoustic vibrations, physical vibrations to the cranium or whole body, electrical stimulation of the mastoid region, vestibular diseases, and drug or alcohol effects impacting the end organs. Many other acceleration perceptions arise by stimulating the vestibular nucleus and associated structures (Goldberg et al., 2011) without directly stimulating the vestibular end organs themselves (e.g., via a moving visual field, which indirectly stimulates vestibular brain centers). Several of the aforementioned methods for inducing acceleration perceptions without using a direct stimulus to the vestibular end organ are promising and should be explored further. Even if many of them do not prove to be viable ways of eliciting consistent and controllable acceleration perceptions in all situations, they must be understood if VE designers are to create effective acceleration simulations that are not inadvertently corrupted by interference from competing stimuli from visual or other modalities. Moreover, using such methods can reduce the requirements for physical motion of the user, which can help to reduce overall space requirements, technical complexity, and cost.

Three promising approaches for eliciting acceleration/motion perceptions were compared in detail in Table 7.1 of Lawson et al. (2002): (1) physical motion of the user (either passively or actively produced), (2) visual stimuli that induce illusions of self-motion, and (3) illusory self-motion induced by locomotion without displacement. Lawson et al. (2002) evaluated the relative advantages and limitations of each of these approaches along 12 dimensions, among which were the range of situations that could be simulated, how compelling or realistic the resulting simulation is, the degree to which the user's activities must be restricted for the desired perception to be elicited, the discomfort associated with the stimulus, and logistic considerations such as expense, technical difficulty, and space requirements. For example, real body acceleration/motion of the user (via moving devices or active real locomotion through a VE) offers the greatest range of situations it can simulate and the greatest realism but is generally the most logistically challenging method to employ and the most likely to induce discomfort if not implemented carefully.

Optimal acceleration simulations will coordinate a variety of vestibular and nonvestibular stimuli so that different cues confirm one another and mutually enhance the simulation (Section 7.6). Presently, the authors recommend that the best VEs for simulating self-motion perceptions will entail simulation-appropriate combinations of (1) real physical motion cues (including motion/tilt devices, vibration, and redirected locomotion), (2) visual, (3) auditory frame-of-reference motion, and (4) illusory locomotion (e.g., walking in place, where real locomotion is not feasible). In addition, the first author believes that judicious application of GVS could be useful in some VE applications (e.g., to simulate recognized spatial disorientation in a flight simulator). If virtual displays are eventually to fulfill the promise of their initial hype and become fully immersive and compelling, it will likely be via a careful combination of the methods outlined earlier.

An important step toward developing a good acceleration simulation involving the vestibular modality is to gain some familiarity with the various vestibular acceleration sensations that are possible and how each one is generated. A wide variety of acceleration perceptions can be elicited via stimulation of the vestibular system, some of which are illusory perceptions. In the succeeding text, most of the categories of acceleration/motion/tilt perceptions involving the vestibular modality are listed, along with a brief description of the stimuli that can cause them. Most of the perceptions described in the following are especially salient when veridical information from nonvestibular modalities is absent (e.g., a helpful earth-referenced visual cue from the outside world is lacking that would have diminished the vestibular effect). The following list of illusions should prove useful for helping VE designers know how to elicit the desired illusions. Just as important, the succeeding information will guide VE designers in knowing which stimuli to avoid in order to prevent unwanted illusions from occurring. The reader should note that the somatosensory system is stimulated also in most of the cases that follows, but the discussion centers on the vestibular system because the dynamics of the vestibular system are important to the dynamics of the illusions and perceptions discussed. An important consideration for most of the methods discussed as follows is that the stimuli can be sickening and so should be used with a full understanding of vestibular reactions and careful design of the motion profile and other sensory conditions of the simulation (e.g., to achieve the purposes of the simulation while limiting the magnitude, duration, and frequency of use of the stimuli).

7.4.1 Perception of Tilt

The simplest way of achieving the feeling of body tilt (i.e., misalignment with the earth vertical) in a VE is to physically tilt the user in the real world at the same speed and by the same amount. The effective stimulus is the change in the direction of the gravity vector relative to the user. When this is not possible or the effect needs to be magnified, one can produce or enhance the feeling of tilt in various ways. For example, a feeling of tilt can be produced by the presence of a linear (including centripetal) acceleration vector not aligned with the gravitational acceleration vector. In a laboratory setting, stimuli for eliciting tilt perceptions in this way include off-center rotation about the vertical axis (leading to a feeling of tilting away from the central axis of rotation) and horizontal linear oscillation at low frequency (leading to a feeling of tilting away from the gravity vector during each deceleration that must accompany a reversal in direction).

In aerospace operations, strong accelerations of the aircraft (e.g., forward thrust during jet-assisted takeoff) can induce a false perception of tilt known as the *somatogravic illusion* (Gillingham & Krutz, 1974). Similarly, an overall increase of the net downward head-to-seat (+Gz)* force (e.g., during a banking turn such as occurs in an aircraft) can cause a complex tilt sensation during head movement (known as the *G-excess effect*; Guedry et al., 1973; Guedry & Rupert, 1991; Chelette, Martin, & Albery, 1992). Rolling back to the straight and level after a prolonged banking turn can cause a pilot to feel a false perception of tilt known as *the leans* (Gillingham & Krutz, 1974).† The feeling of self-inversion is a special case of perceived tilt. A perception of inversion can be induced in a VE by turning the user upside down, or it can be done by less direct means. Turning a user upside down in a VE could augment the ground-based simulation of the inversion illusion that may occur in real aviation operations when a transition from higher to lower (or negative) G-force occurs (e.g., climbing followed by rapidly leveling off or diving; entry into weightlessness; Graybiel & Kellog, 1967). The same technique could be used to simulate the inversion illusions that can occur during the sudden removal of downward forces that occurs upon transition to microgravity during parabolic flight or entry into space flight (Nicogossian, Huntoon, & Pool, 1989).

7.4.2 Perception of Rotation

The simplest way to achieve a feeling of rotation (or other curvilinear motion) in a VE is to move the user in a rotating (or other curved) path that exactly duplicates the intended simulation. When an

* Positive Gz refers to a downward force (caused by upward acceleration) along the longitudinal axis of the head and body. Negative Gz refers to an upward force (caused by downward acceleration) in the longitudinal axis. The three cardinal head axes used in vestibular research are as follows (Hixson et al., 1966): (1) The z-axis is a dorsal–ventral (or cephalocaudal) line traveling along the intersection of the midcoronal and midsagittal planes and is commonly called *yaw* (for angular acceleration about this axis) or *heave* (for linear acceleration within this axis); (2) the x-axis is an anterior–posterior (or naso-occipital) line traveling along the intersection of the midsagittal and midhorizontal planes and commonly called *roll* (for angular acceleration) or *surge* (for linear acceleration); and (3) the y-axis is an interaural line traveling along the intersection of the midcoronal and midhorizontal planes and commonly called *pitch* (for angular acceleration) or *sway/sideslip* (for linear acceleration).

† Related phenomena such as the *graveyard spin*, *graveyard spiral*, and *giant hand phenomenon* were originally described by researchers such as Graybiel, Benson, and Gillingham. A history of this area of research and description of each illusion is provided in Previc and Ercoline (2004).

illusion of rotation is caused by rapid deceleration following prolonged unidirectional rotation in the darkness, it is called after-rotation. The after-rotation sensation involves a feeling of turning opposite to the direction of prior body rotation when the prior body rotation was passively generated, but when the body rotation is actively generated (by stepping around in a circle), the after-rotation illusion is diminished and may be felt in the same direction as prior rotation (Guedry, Mortenson, Nelson, & Correia, 1978).

When an illusion of rotation is caused by a sudden motion of the head in an axis not parallel to the central rotation axis of the body during prolonged rotation in the darkness, it is called a *Coriolis, cross-coupling* effect and is characterized by a feeling of head or self-velocity in a curved path that is predominantly (Lawson, 1995) orthogonal to the axes of both body and head rotation (Guedry & Benson, 1978; Newman, Lawson, Rupert, & McGrath, 2012). The aforementioned (see Section 7.4.1) feeling of tilt vis-à-vis gravity that arises from a purely linear acceleration (usually via low-frequency oscillation) in a horizontal plane is also a perception that has an angular component because the resultant of acceleration due to gravity and due to horizontal movement creates a rotating gravitoinertial acceleration vector that is perceived as an angular change in the direction of *up* when earth-referenced visual cues are absent or fixed relative to the observer (Howard, 1986a,b). Note that these stimuli should be used with caution and careful design of the simulation.

7.4.3 Perception of Translation

When users' actions within a VE require them to move in a straight line, one can move them through the physical world passively or actively (Section 7.5.3) in the same manner. However, given the limited size of most buildings' housing VE displays, often it is desirable to create the illusion of moving in a straight path over a longer time and distance than is physically possible. Such a magnified movement perception can be accomplished via the use of a centrifuge, albeit with the introduction of some angular acceleration. The centrifuge technique is especially useful when the device can minimize the undesirable consequences of angular acceleration by employing the longest feasible rotation radius and allowing for strategic combinations of radial linear translation (toward or away from the center of rotation) and capsule-centered counterrotation (on-axis capsule rotation opposite to the direction of rotation of the central axis of the centrifuge) during the off-center rotation stimulus. (For an explanation of these complex stimuli, see Hixson, Niven, and Correia, 1966.)

It is also possible to elicit translation illusions without a centrifuge. During off-vertical rotation at certain frequencies, participants may experience conical or orbital paths of self-motion of considerable radius, where little or no real translation is occurring (Lackner & Graybiel, 1978; Wood, 2002). However, these stimuli should be used with caution and careful design of the simulation.

7.4.4 Illusory Absence of Tilt

In this case, one has the illusion of remaining in one's former orientation vis-à-vis gravity when one has actually tilted. This can occur when the tilt stimulus is below the threshold of detection, estimates of which vary widely, with some as low as 1.7° of tilt, depending upon the exact stimulus and cues (Lewis, Preiesol, Nicoucar, Lim, & Merfeld, 2011; Mann, Dauterive, & Henry, 1949; Nesti, Masone, Barnett-Cowan et al., 2010; Bringoux, Scherber, Nougier et al., 2002). Tilt can also fail to be perceived when the participant remains aligned with the resultant gravitoinertial force vector during off-center rotation, such as occurs during a banking turn in an airplane (Gillingham & Krutz, 1974).

A failure to detect tilting of the resultant gravitoinertial force vector can occur when the individual remains seated upright while rotating off-center at a very low velocity (wherein the threshold for stimulation given by the oculogravic illusion would suggest that a tilt of the resultant that is less than 1.1° would be undetectable, according to Graybiel and Patterson, 1955). Finally, during off-vertical rotation at frequencies near 0.2–0.3 Hz (Denise, Etard, Zupan, & Darlot, 1996; Golding, Arun, Wotton-Hamrioui, Cousins, & Gresty, 2009), the feeling of rotating in a tilted axis can be replaced by a feeling of moving orbitally in a fixed plane with little or no rotation occurring. For example, subjects rotating about a spine-centered z-axis that is tilted 20 relative to the gravitational vertical may instead feel they are upright and are orbiting in a horizontal plane with their noses pointing at one wall of the room throughout. Similarly, participants lying down and rotating about an earth-horizontal longitudinal z-axis or even seated and pitching end over end about a horizontal (e.g., interaural) y-axis may feel upright (Lackner & Graybiel, 1977; Leger, Landolt, & Money, 1980). Note that these stimuli require caution and careful design of the simulation.

7.4.5 Illusory Absence of Rotation

One can be moving in a curved path but experience the illusion of moving in a straight path or of not moving at all. This effect can occur during off-center rotation below the threshold of the semicircular canals. The minimum threshold for rotation sensation is around 0.44°/s^2 using verbal reporting of self-rotation but can be as low as 0.11°/s^2 when detection of the oculogyral illusion is used as the threshold measure (Clark & Stewart, 1968). Even when the rotation stimulus is above threshold, it is possible to fail to perceive a part of the rotation stimulus during off-center angular acceleration with the nose (x-axis) aligned with the resultant of the tangential and centripetal acceleration vectors (Guedry, 1992). A failure to perceive self-rotation can also occur after prolonged constant-velocity rotation because the elastic properties of the cupula of the semicircular canal will cause it to return to resting position during prolonged constant-velocity rotation. The user will feel stationary in this situation if there are no veridical visual (or other nonvestibular) cues to inform him or her that he is still turning. Finally, failure to perceive rotation can occur when rotating with the longitudinal z-axis of the body orthogonal to gravity (e.g., rotating as if on a horizontal barbecue spit). At certain frequencies, this stimulus results in a feeling of orbital motion of the body about a horizontal axis located at a radius from the body, with little or no change in the direction one's face seems to point and hence no negligible felt *rotation* about one's own longitudinal z-axis (Lackner & Graybiel, 1977). Similarly, rotation about an earth-horizontal y-axis at certain frequencies elicits the illusion of orbital motion without rotation, known as the Ferris wheel illusion (Mayne, 1974; Leger et al., 1980). Note that these stimuli require caution and careful design of the simulation to avoid motion sickness.

7.4.6 Illusory Absence of Translation

In this instance, one has the illusion of not moving in a straight line when one is doing so. This effect can be produced by linearly translating an individual (without tilting his or her body out of its former alignment vis-à-vis gravity) below the threshold of the otolith organs, which is about 6 cm/s^2 (Melvill-Jones & Young 1978), but may be slightly lower for participants oriented sideways to the movement (i.e., translating along the y-axis; Melvill et al., 1978; Travis & Dodge 1928). Note that when the linear translation exceeds the threshold of detection, both translation and tilt can be experienced (due to the changing direction and magnitude of the resultant gravitoinertial vector).

7.4.7 Perception of Increased Weight or G-Forces

When driving a real vehicle such as a car or an airplane, one is subjected to G-forces during acceleration in various directions. However, in most current VE, these forces are absent during simulated driving or flying. This absence should be no surprise when one considers the problem of simulating a high-performance jet aircraft. For example, to simulate the forces during a catapult launch takeoff from an aircraft carrier, one would need a simulator and a maneuvering space several hundred feet long. Fortunately, G-force can also be created via centrifugation. One can readily reproduce most of the perceptual aspects of a catapult launch takeoff in a much smaller space by rotating the pilot off-center inside a centrifuge capsule while keeping his nose pointing into (i.e., his x-axis aligned with) the resultant of the tangential and centripetal acceleration vectors (Guedry, 1992). The predominant perception will be of rapid forward and upward acceleration while pitching back. Another way to produce the feeling of changing aircraft G-forces during centrifugation is by exploiting the linear Coriolis acceleration that occurs when a body is moved radially in a rotating environment. Due to the inertia of the body, a force tangential to its motion will act on it during (actual) displacement toward or away from the center of rotation. This method will produce a force that is dependent upon factors such as the speed of rotation of the environment and the mass and speed of the user. Coriolis acceleration should be taken into account whenever simulating aircraft G-forces on a centrifuge that permits radial capsule motion.

7.5 ROLE OF ISOMORPHIC *REAL*-MOTION STIMULI

Even the most careful orchestration of visual displays, locomotion devices, and man-moving machines will not provide an acceleration experience that can pass the virtual reality Turing test (Barberi, 1992; Turing, 1950) for all of the synthetic experiences in a given VE's repertoire. There is a way of simulating real events that has the potential to elicit acceleration perceptions that are indistinguishable from reality, however. This method involves identically duplicating the real acceleration profiles being simulated, but doing so in an alternate real location (e.g., a simulation facility) from the user's virtual location (e.g., a simulated battleground). This isomorphic method is similar to the concept of augmented reality, wherein users see and move through a real environment while being able to view virtual information as well. However, the purpose of the isomorphic simulation presently under consideration is not to provide additional information to a user who is otherwise engaged with the physical world. Rather, the goal is to provide a physical mock-up that serves as the ambient context for a synthetic event that would be difficult or impossible to experience in the physical world. What follows are several potential applications of isomorphic motion stimuli for practical purposes, such as enhancing flight training and law enforcement training.

7.5.1 Applying Isomorphic Real Acceleration to Enhance Aviation Mission Rehearsal

During advanced mission rehearsal, military aviators flying real aircraft would execute all the same maneuvers and actions as they would execute during a real combat mission, except they would fly in a designated friendly airspace. The flying would be real, but the targets, threats, and ordnance would be simulated. Aviators would view simulated targets and simulated ground or air threats through virtual displays and neutralize them either through virtual representations of weapons systems or via live fire on real practice targets whose position in a safe location coincides with the virtual image and virtual targeting information represented to the pilot. Opponents could also be real but remote (e.g., aviators and air defense personnel from allied countries coordinating in the exercise from their own friendly airspaces). Safety of the crew and allied ground troops would be ensured by simulating (or deactivating) ordnance in all situations involving close support of ground troops and by close monitoring from the ground and from an onboard safety observer who is not part of the VE. This approach would allow for more realistic, varied, and challenging practice than is possible with current simulators or small-unit training exercises. It would also provide many of the training benefits of full-scale war games on a more frequent basis and without the same amount of preparation time, cost, danger, environmental impact, or political visibility (useful in cases where demonstration of force is not a mission goal). Even as unmanned, remotely controlled systems become increasingly important in military and civilian applications, appropriate motion cues will be desirable to enhance situation awareness concerning the moment-by-moment state of the unmanned vehicle under control (so as to aid tasks requiring mental rotation, avoid a control reversal error, etc.).

7.5.2 Applying Isomorphic Real Acceleration to Enhance Automobile Racing Rehearsal

Race car drivers routinely practice alone on tracks to familiarize themselves before a race. Using virtual displays, it would be possible for drivers to do practice runs against virtual (real or simulated) competitors represented on an otherwise transparent (*look through*) display while driving alone on a real track at a speed reduced just enough to keep the margins of exposure to monetary and personnel risk appropriate to the practice session. If the driver makes a driving error while maneuvering against a simulated (or real but remote) competitor, he will receive error feedback but will not suffer a dangerous and expensive car-to-car collision. This type of practice would form a bridge between lone practice on the track and live competition with other drivers. It could also save lives by familiarizing drivers with hazardous episodes of driver disorientation that can be caused by excessive G-forces (Guedry, Raj, & Cowin, 2003).

7.5.3 Applying Isomorphic Real Acceleration via Free-Space Walking in a VE

Allowing for natural walking in real space during VE use is probably the most intuitive and straightforward way for navigating computer-simulated environments and readily provides the appropriate vestibular and somatosensory self-motion cues. In this approach, users wear position and orientation tracking head-mounted displays (HMDs) that allow the system to match their physical locomotion with visual scene cues. When optic flow is displayed on an HMD, it can significantly influence human walking and is readily integrated with vestibular and somatosensory cues (Warren, Kay, Zosh, Duchon, & Sahuc, 2001). Foxlin (2002) provides an overview of the challenges and technological requirements involved in providing low-latency motion tracking over extended free-space walking areas.

Apart from being a natural and intuitive way to move through VEs, allowing users to naturally walk can increase the naturalness and presence of a VE simulation, compared to simpler locomotion methods like walking in place or button-based navigation (Usoh et al., 1999). When rapid and efficient (i.e., naturalistic) navigation is required, actual walking outperforms joystick-based motion metaphors (Suma et al., 2010). Walking in VE can also help to improve user's navigation ability and reduce disorientation (Chance, Gaunet, Beall, & Loomis, 1998; Ruddle & Lessels, 2009), although merely allowing the user to turn naturally can sometimes be sufficient to provide many of these benefits (Riecke et al., 2010).

Walking in a VE typically requires wearing an HMD, which frequently results in an underestimation of visually presented distances (Creem-Regehr, Willemsen, Gooch, & Thompson, 2005; Loomis & Knapp, 2003). While the underlying reasons are not fully understood, recent work suggests that this systematic distance underestimation can be compensated for by artificially increasing the simulated FOV beyond the physical FOV of the HMD (Zhang, Nordman, Walker, & Kuhl, 2012) or by enhancing visual motion (with moving particles, sinus gratings) in the periphery of the stimulus to increase perceived self-motion (Bruder, Steinicke, & Wieland, 2011; Bruder, Steinicke, Wieland, & Lappe, 2012).

While it seems desirable to simply allow users to walk through VEs whenever possible, there are several technical and perceptual challenges (Steinicke et al., 2013). One of the most critical challenges is how to simulate and navigate a sufficiently large virtual space when the physical space in which users can walk around with head-tracked HMD is severely limited. Several approaches have been suggested to tackle this challenge (Steinicke et al.), and this chapter highlights some of them, for example, subtly redirecting users' walking trajectories such that they stay within the physical confounds using redirected walking (Section 7.5.5) or variants of walking in place using linear or circular treadmills (Section 7.2.3). In the following discussion, we briefly present one example of a practical training application where free-space walking in a VE would be beneficial.

7.5.3.1 Applying Real Locomotion through Simulated Environments as Part of Police Training

In traditional video-based training simulations, self-motion was suggested solely by the visual stimulus, and *movement* was scripted in advance, based on options selected by the user. Even in some current devices where movement is not scripted, the user's navigation and visual reconnaissance may be accomplished via nonintuitive methods such as foot switches that initiate visual scene motion, the direction of which is then determined by head pointing. One of the key features distinguishing future individual (or small unit) combat simulations will be that body movement through the VE will be realistic and naturally accomplished.

Law enforcement officers serving on special weapons and tactics (SWAT) teams could go armed into a physical mock-up of a house and proceed to *clear* the armed and hostile criminals resisting within (e.g., as part of hostage crisis training). This simulation would be achieved via voluntary movement through the typical *fun house* or *Hogan's Alley* (a custom-built practice area that looks like a regular building but has bullet-resistant backstops all around to enhance the safety of live-fire practice), coupled with head-mounted *look-through* visual displays wherein virtual criminals and bystanders (either computer simulations or real-but-remote users sharing the VE) appear suddenly and either respond to certain key verbal commands or attempt to attack the officers with various simulated weapons. The performance score of the trainee would be based on his or her speed and skill in moving through the simulation (e.g., skill with *quartering techniques* when rounding corners or entering rooms, use of cover and concealment) and speed in neutralizing threats with appropriate force (e.g., coordination with other officers, skill with nonlethal force alternatives, accuracy and speed of shooting).

Simulation of return fire could be based on tracking technology on the bodies and weapons of two opposing teams of officers moving through one virtual space but physically located in different practice areas. The simplest example would be the case where one officer is locomoting through the Hogan's Alley and directing live fire against the virtual representation of another officer playing the role of a violent criminal in a different Hogan's Alley. The approach described is a marriage of multiplayer tactical shooter or virtual battlefield gaming concepts (e.g., Virtual Battlespace Systems) with training simulations already in use to allow live fire against projected images of prerecorded actors or programmed computer characters portraying criminals (http://teams.drc.com/fast/index.html) and simulated fire against live opponents (www.ais-sim.com; www.meggitttrainingsystems.com). As the most useful features of these existing techniques are enhanced by the new virtual display features previously mentioned, more sophisticated and realistic simulations will emerge. Even though automated virtual avatars are growing more complex (Biron, 2012), having the option for human-to-human engagement will yield clear advantages for the training of law enforcement personnel and for certain national defense applications (Finkelstein, Griffith, & Maxwell, 2014, Chapter 37). The situation is somewhat analogous to the way massively multiplayer online first-person-shooter games replaced games where competition was only possible with the computer.

7.5.4 Advantages and Limitations of Using Isomorphic Acceleration/Motion Stimuli

Real acceleration provides the most direct means for eliciting acceleration perceptions in VE and allows incredible flexibility and control concerning the types of acceleration perceptions that can be elicited at any given moment. Real acceleration that is isomorphic to the psychophysics of the VE should minimize the amount of interference a VE trainer creates regarding the transfer of psychomotor skills to a real situation. For example, if the aircraft-based VE previously mentioned (see Section 7.5.1) is designed and executed properly, it will be able to simulate a hazardous military combat mission over friendly airspace, eliciting only those adaptive effects and aftereffects that occur during a comparable real flight.

The primary disadvantage of using real acceleration in VE is that this approach will require large and often costly practice spaces. In the case of military flight training, this concern is not insurmountable because the infrastructure for real flying (of simulated missions) is already in place (albeit fuel is a significant factor). For police training, the infrastructure of *fun houses* is also in place among many of the larger agencies, although numerous software challenges remain in order to enhance realism and simulate the stress of actual operations. For smaller applications, the introduction of redirected walking techniques (Section 7.5.5; Steinicke, Bruder, Jerald, Frenz, & Lappe, 2010) can reduce the size of the space required, provided the physical mock-up is simple or highly flexible.

The cost associated with introducing real acceleration into VE training for the most popular professional or Olympic sports will probably be less of an impediment than it is for the military and law enforcement. However, the technical ease of implementation and the revenue available for implementation of virtual acceleration or motion will be very different for different sports. For example, implementation of virtual acceleration/motion training could be achieved readily for either automobile racing or whitewater kayaking but would probably be implemented for automobile racing first (despite the fact that a larger practice area is necessary), because automobile racing has greater spectator and commercial support (and thus commands greater revenue). Also, virtual acceleration/motion training during automobile racing can be accomplished on existing automobile tracks without substantive modifications to the track itself, whereas the simulation of whitewater kayaking requires the construction of a special recycling water course with programmable high-speed currents. Some sports will be very difficult to train for via real movement through virtual spaces. A good example would be equitation, which requires the mutual coordination of perception and action on the part of a horse and rider, each of whom has profoundly different user requirements.

7.5.5 Offering Fairly Isomorphic Acceleration Stimuli in a Smaller Space via *Redirected Walking*

How can we naturally walk through large virtual spaces without bumping into the physical walls or leaving the designated area wherein movements can be tracked? To solve this space and safety challenge, various redirected walking techniques have recently been developed and refined. While *repositioning techniques* aim to compress the VE into a more constrained physical space, *reorientation techniques* try to subtly steer users away from the physical boundaries that users might otherwise bump into (see taxonomy by Suma, Bruder, Steinicke, Krum, & Bolas, 2012). When the real space is only slightly smaller than the to-be-simulated virtual space, simple continuous repositioning by using a gain factor between virtual (simulated) and actual (walked) distance might be sufficient; by measuring detection thresholds, Steinicke et al. (2010) showed that walked distances could be upscaled by up to 26% or downscaled by up to 14% without users noticing this discrepancy. When larger simulated environments are needed, there are multiple options. Users could be repositioned by employing real-word metaphors like elevators, escalators, or various vehicle types to reduce disruptions. For longer distances, *teleportation* can provide a possibility, especially if metaphors inspired by science fiction such as portals are employed to provide a consistent motion framework, such as in the Arch-Explore natural user interface for architecture explorations proposed by Bruder, Steinicke, and Hinrichs (2009). Apart from repositioning techniques, various user reorientation techniques can also be used to trick the user into remaining within the physical boundaries, ideally without noticing that they are being redirected. The most promising approaches involve continuous subtle reorientation techniques, which exploit the fact that users are not very accurate in estimating the angle through which they have actually turned. For example, users can be made to believe that they are walking on a straight path despite being redirected on a fairly circular path. While promising, this still requires a curvature radius of a least 22 m and thus will not by itself fit into most current free-space walking areas (Steinicke et al.). When the simulation does not require or afford long straight paths, however, it can become possible to continuously and smoothly adjust the gain factors between virtual and physical rotations and translations to ensure that users stay within the physical boundaries. In fact, our perception of rotations seems to be more malleable than our perception of translations; in a detection threshold study, users did not notice any difference when physical rotations were up to 49% larger or 20% lower than the perceived simulated rotation (Steinicke et al.). This extends earlier findings of often surprisingly large coherence zones where visuo-vestibular cue mismatches remain unnoticed or have only negligible impact (Steen, 1998). Especially when users' attention can be directed away from the locomotion itself, the coherence zone might be further increased. For example, Hodgson, Bachmann, and Waller (2011) steered users to walk arcs with curvature radiuses as low as 8 m without the majority of users noticing any discrepancy. Even those who did notice some discrepancy did not seem to mind or be affected much. This allowed Hodgson et al. (2011) to develop a first generalized redirected walking algorithm that can dynamically steer users away from the physical boundaries while they are exploring a VE. While some users detected discrepancies between real and simulated motions, their spatial memory of the VE remained unaffected, which is promising for future applications.

From an applied perspective, benefits and costs of various redirected walking procedures should be carefully evaluated, since they tend to be specific to the task and goals of the simulation. For some VE goals, walking would not be essential. Naturalistic visual cues in immersive VE can sometimes be sufficient for enabling rapid and effective spatial orientation despite the lack of physical motion cues (Riecke, Cunningham, & Bülthoff, 2007; Riecke, von der Heyde, & Bülthoff, 2005), although there can be individual differences between users (Riecke, Sigurdarson, & Milne, 2012). When physical motion cues are relevant and larger distances need to be covered, walking can be flexibly integrated with redirected driving methods where larger sensory discrepancies can remain unnoticed (Bruder, Interrante, Phillips, & Steinicke, 2012). Methods developed for optimizing redirected walking algorithms can also provide useful guidance for improving driving or even flight simulation, where coherence zones tend to be larger and thus allow for more flexibility.

Finally, when budgetary or spatial constraints are tight, the requirements for physical (loco)motion can be reduced by exploiting multimodal synergistic effects (see also Sections 7.2 and 7.6). In particular, naturalistic full-field visual stimuli can provide compelling self-motion illusions in the absence of any physical motion (Riecke, 2011; Riecke, Schulte-Pelkum, Avraamides, Heyde, & Bülthoff, 2006; Wright, DiZio, & Lackner, 2006). The potential of the visual modality is probably best demonstrated in *tumbling rooms*, where stationary observers may report tumbling sensations of 180° (head down) or greater (full revolutions) when an immersive room is rotated around them (Allison et al., 1999; Howard & Childerson, 1994; Howard, Jenkin, & Hu, 2000; Palmisano, Allison, & Howard, 2006). Thus, the motion paradigm and simulated modalities should be carefully selected on a case-by-case basis to best suit the specific task, context, and overall simulation goal (Riecke & Schulte-Pelkum, 2013).

7.6 BENEFIT OF COMBINING DIFFERENT SENSORY CUES

A controlled and convincing feeling of acceleration and self-motion within a VE can be achieved via a judicious combination of the more promising stimuli listed earlier. Multimodal inputs act in concert to create acceleration perceptions in the natural world. Similarly, perceptions of motion in VE can be enhanced by exploiting coordinated combinations of multimodal stimuli. For example, feelings of acceleration and self-motion can be significantly enhanced when motions of the visual field (see Section 7.2.1) correspond with real motions of the user (Sections 7.4 and 7.5; also Wong & Frost, 1981; Young, Dichgans, Murphy, & Brandt, 1973). When large-scale movements of the user are not feasible or affordable, visually simulated self-motions can be enhanced by small-scale passive physical motions of the body (e.g., simple jerks or more sophisticated motion cueing of a few degrees or centimeters) that corroborate the visually indicated self-motion (Berger, Schulte-Pelkum, & Bülthoff, 2010; Riecke, 2006; Schulte-Pelkum, 2007; Wright, 2009; Wright, DiZio, & Lackner, 2005). Similar benefits can be gained when users themselves initiate and power the motion cueing, for example, by seating people on a modified force-feedback manual wheelchair (Riecke, 2006) or a gaming chair where participants control the virtual locomotion by leaning into the direction they want to travel (Beckhaus, Blom, & Haringer, 2005; Riecke & Feuereissen, 2012). While vibrations (see Section 7.2.3.3) or jerks separately can enhance visually induced percepts of self-motion, combining vibrations and jerks provide additional benefits (Schulte-Pelkum, 2007).

Spatialized sound (Section 7.2.2) can enhance perceptions of self-motion induced by cues from vision (Section 7.2.1; also Riecke et al., 2005; Riecke et al., 2009), somesthesia (Section 7.2.3; also Riecke et al., 2011), or vestibular sensation (Sections 7.2.4, 7.3 through 7.5).

There is mixed evidence concerning whether linear treadmill walking can facilitate visually induced sensations of self-motion (Ash et al., 2013; Kitazaki et al., 2010; Onimaru et al., 2010;

Seno et al., 2011). However, walking on circular treadmills can by itself reliably induce acceleration and self-motion percepts (Bles, 1981; Bles & Kapteyn, 1977; Bruggeman et al., 2009; Riecke et al., 2011) and so should work well with visual cues (Freiberg, Grechkin, & Riecke, 2013), possibly further enhanced by matching moving sound fields (Riecke et al.) as discussed in Section 7.2.3. Moreover, adding matching rotating sound fields can enhance kinesthetic vection in this situation (Riecke et al.) and induce self-motion illusions that are strong enough to facilitate perspective switches (Riecke, Feuereissen, Rieser, & McNamara, 2012). That is, while it is difficult to imagine an orientation change in our immediate environment without physically rotating to the new perspective, the mere illusion of self-rotation was sufficient to facilitate this perspective switch, even in the absence of any supporting visual cues. While further studies are needed to confirm and extend these findings, they suggest that providing compelling sensations of self-motion in VE may help people to remain oriented to the VE during simulated (but not physically executed) self-motions. In our view, the most promising methods for inducing self-motion and acceleration illusion perceptions in a VE will tend to combine three or more of the following stimulus types, in a mutually supporting manner appropriate to the specific purposes of the simulation and the VE designer: (1) visual frame-of-reference motion, (2) auditory surround motion, (3) somatosensory cues, and (4) vestibular cues, including passive body acceleration, active body movement, and/or vestibular stimuli not requiring acceleration (especially electrical stimulation).

7.7 VISUAL CONSEQUENCES OF ACCELERATION

This chapter is concerned with the perception of body acceleration and motion. However, it should be noted that many acceleration stimuli can influence the perception of a visual target or display relative to the user. For example, simple body tilt in darkness can make it hard for an observer to set a line of light to align with the true earth vertical. The visual effects of acceleration stimuli include the following: the Müller (or *E*) effect, the Aubert (or *A*) effect (e.g., Bauermeister, 1964; Clark & Graybiel, 1963; Müller, 1916; Passey & Ray, 1950; Wade & Day, 1968), the oculogyral illusion (Graybiel & Hupp, 1946), the oculogravic illusion (Graybiel, 1952), the elevator illusion (Cohen, 1973; Whiteside, 1961), and the degradation of visual acuity that occurs when viewing a head-fixed display while one's body is moving (Guedry, Lentz, Jell, & Norman, 1981). Thus, even when a user is being exposed to a simple tilt, the VE designer must take into account the interactions between visual inputs and vestibular and somatosensory inputs for any task requiring visual estimates of the orientation of objects within the virtual scene or any tasks requiring eye-to-hand coordination. Fortunately, many of these effects will be minimized by the presence of a whole-field visual stimulus (rather than a simple visual target presented in the darkness, as in most of the laboratory studies cited). This will be true especially when the visual stimulus provides veridical information about self-orientation (Lawson et al., 1997).

7.8 COGNITIVE INFLUENCES

Cognitive aspects of the simulation can improve the overall believability and effectiveness of motion simulations (for reviews, see Riecke, 2009, 2011; Riecke and Schulte-Pelkum, 2013). For example, visually simulated self-motions can be facilitated when the moving visual cues are perceived as background motion with respect to an observer-fixed foreground, even when there is no physical depth separation (Brandt et al., 1975; Ito & Shibata, 2005; Kitazaki & Sato, 2003; Nakamura, 2008; Nakamura & Shimojo, 1999; Ohmi & Howard, 1988; Ohmi, Howard, & Landolt, 1987; Seno et al., 2009).

Priming users to believe that physical motion is possible can also enhance visually induced self-motion percepts (Andersen & Braunstein, 1985; Lepecq, Giannopulu, & Baudonniere, 1995; Wright et al., 2006), thus confirming earlier assertions that knowledge that actual motion is impossible might be detrimental to inducing vection (Dodge, 1923). This technique is frequently employed in entertainment applications such as theme park fun rides, where physical setups and narratives are combined to provide a cognitive-perceptual framework that makes actual motion seem possible.

7.9 SUMMARY

The perception of acceleration encompasses feelings of self-motion through space and self-tilt relative to the upright. The feeling that one is being subjected to unusual forces (such as occur during high-performance flight or in nonterrestrial settings) also qualifies as an acceleration perception. The techniques for eliciting acceleration perceptions in future VEs will employ either real motion or illusory motion. Real-motion methods will accelerate the VE user aboard a moving device such as a centrifuge or will allow the user to drive or actively locomote (as appropriate) within a real space that serves as an ambient context for the VE. Illusory motion methods will induce an illusion of body motion by moving a visual, auditory, or somatosensory surround stimulus relative to the user or by having the user locomote (without displacement) on a treadmill or similar device. Each of these methods has advantages and limitations that have been discussed. The methods for inducing acceleration perceptions via real motion will tend to generate a wider range of simulations and be more effective. The methods involving illusory motion will require less money and space to implement. Methods employing real or illusory motion are not mutually exclusive. When a person moves through space while receiving visual, auditory, or somatosensory information that confirms the movement, the resulting movement perception will tend to be stronger than when only one self-movement cue is present in isolation. Thus, combining different cues to elicit acceleration perceptions will be advisable whenever it is feasible. Such multisensory cueing is exactly what takes place whenever the reader goes for a stroll through the real world.

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APPENDIX: RECOMMENDED READINGS ON VESTIBULAR FUNCTION

7.A.1 Basic Reviews

For a simple and clear introduction to the perception of body position and movement via kinesthesia and vestibular sensation, the authors recommend the textbook by Ludel (1978). For more detailed explanation of acceleration stimuli and acceleration perceptions, see Nicogossian et al. (1989), Guedry (1992), or Previc and Ercoline (2004). Classic scientific reviews on vestibular sensation were written by Guedry (1974) and Howard (1986a,b). The comprehensive paper by Guedry (some of which is updated in Guedry, 1992) focuses on psychophysics of vestibular sensation during a wide variety of stimulus situations. The 1986b paper by Howard provides a lucid review of vestibular structure, dynamics, neural projections, and psychophysics, ranging afield of the vestibular modality as well.

7.A.2 Reviews on Spatial Orientation in Flight

The most comprehensive recent review of this subject was contributed by Previc and Ercoline (2004). This book covers all the aviation aspects of spatial orientation. The classic introductory papers written on spatial disorientation vis-à-vis aerospace operations were contributed by Benson (1988) and by Gillingham and Krutz (1974). Another classic resource is Guedry's Chapter 8 of the 1968 U.S. Naval Flight Surgeon's Manual. This is a thorough effort with a clinical slant. The most recent online version of this manual is at http://www.operationalmedicine.org/TextbookFiles/USNavalFlightSurgeonsManual.htm. These various works introduce the common illusions associated with spatial disorientation in flight, common vestibular acceleration nomenclature, and human reflexive reactions to unusual accelerations, especially high G. For recent reviews focused on vestibular problems during spaceflight, see Clément (2011) and Buckey (2006).

7.A.3 Detailed Research Compendia or Books Treating Special Topic Areas

Many works on vestibular function are from special edition compilations of papers or chapters by various scholars. Works of note include Cohen, Tomko, and Guedry (1992), Arenberg (1993), and Marcus (1992). The book by Cohen, Tomko, and Guedry covers a variety of topics on vestibular and sensorimotor functions. Arenberg gives a thorough treatment of dizziness and balance disorders. The most comprehensive new scientific review has been contributed by Goldberg et al. (2011). The book by Goldberg et al. covers topics beyond vestibular pathology but has a strong neurophysiological emphasis, rather than a perceptual emphasis geared for VE designers.

7.A.4 Works on Side Effects of Virtual Environments

The latest information on adverse side effects of VE exposure and most other human factor issues related to VE can be found throughout this second edition of the Handbook of Virtual Environments (Hale & Stanney, 2014). Earlier sources for information on unpleasant vestibular side effects relevant to VE include Pausch, Crea, and Conway (1992); Chien and Jenkins (1994); Durlach and Mavor (1995); Kolasinski (1995); Stanney, Mourant, and Kennedy (1998); and Stanney et al. (1998).

7.A.5 General Human Factor Reference Works of Relevance to Orientation

The *Handbook of Human Factors and Ergonomics* (Salvendy, 2006) is a good general reference that briefly touches upon vestibular displays and vestibular effects (in Chapters 40 by Stanney and Cohn or Chapter 23 by Griffin). The older *Engineering Data Compendium: Human Perception and Performance* is a multivolume set edited by Boff and Lincoln (1988). This compendium of human factor findings has succinct sections devoted to orientation, vestibular function, and simulation.

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