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Simulator and Scenario Factors Influencing Simulator Sickness

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Abstract

The Problem. The consequences and implications of simulator sickness for the validity of simulation can be severe if not controlled and taken into account (Casali, 1986). Many of today's driving simulators are used to perform research, training, or proof of design activities. A prerequisite to generalizing the results found in research conducted in a simulator is an understanding of the validity of the resulting experience. Without question, simulator sickness is a factor that can affect the validity of research simulators. Given the potential consequences of simulator sickness, it is difficult to assess the value of the results obtained from a simulator study known to have significant sickness problems. ***Role of Driving Simulators.*** There are alternatives to driving simulators for studying most, if not all, issues. However, these alternatives are often unsafe, do not provide a well-controlled environment, and require large sums of money to implement. Thus, driving simulators are necessary and the associated issues of simulator sickness need to be addressed. ***Key Results of Driving Simulator Studies.*** Simulator sickness can affect a driver's performance in a variety of negative ways due to inappropriate behaviors, loss of motivation, avoidance of tasks that are found disturbing, distraction from normal attention allocation processes, and a preoccupation with the fact that something is not quite right. On the positive side, simulator selection, participant screening, scenario design, and control of the environment can all reduce the incidence of simulator sickness. ***Scenarios and Dependent Variables.*** Examples of the sorts of scenarios that lead to extremes of simulator sickness are discussed. Additionally, the various measures that have been used against simulator sickness are highlighted, including some with predictive validity. ***Platform Specificity and Equipment Limitations.*** Simulator sickness appears to be most extreme in fully immersive environments and when head-mounted displays are used. A motion base does not necessarily reduce simulator sickness symptoms.

14.1 Introduction

Simulator sickness or the report of ill feelings associated with the use of simulation devices has been a persistent challenge for simulator-based research. Simulator sickness is not limited to any one type of driving simulator. It is has been documented on both floor and head-mounted simulators (Draper, Viirre, Furness, & Gawron, 2001; Draper, Viirre, Furness, & Parker, 1997; Ehrlich, 1997); and among floor-mounted simulators it has been observed in both motion-base and fixed-base simulators. Casali (1986) noted that documentation of simulator sickness can be found in reports by Havron and Butler as early as 1957 in a helicopter flight training simulator. In these early reports, the phenomenon was reported as motion sickness or the result of exposure to low frequency, whole body motion. Both motion sickness and simulator sickness can result in an array of symptoms including eye strain, headache, postural instability, sweating, disorientation, vertigo, pallor, nausea, and vomiting (Ebenholtz, 1992; Pausch, Crea, & Conway, 1992). Kennedy et al. (1987) provide a full categorization of the symptoms associated with simulator sickness.

Although the symptoms are common between motion and simulator sickness, they are not identical. Casali (1986) makes the distinction based on research conducted by Money (1970), suggesting that stimulation of the vestibular system is required to induce motion sickness. Consistent with this, there are many reports of simulator sickness and related symptoms in fixed-based simulators that include no physical motion cues. Therefore, a distinction between motion and simulator sickness is useful because it is not only the actual physical motion that can cause sickness. It appears that some visual stimuli, likely perceived motion or vection, can also contribute to simulator sickness (Kennedy, Hettinger, & Lillenthal, 1988). Indeed, there are a number of factors that contribute to simulator sickness, a fact that led Kennedy and Fowlkes (1992) to describe simulator sickness as a syndrome because it has many complex contributing causes and manifests itself with many potential symptoms. A good discussion of contributing factors can be found in Kolasinski (1995).

The consequences and implications of simulator sickness on the validity of simulation can be severe if not controlled and accounted for (Bittner, Gore, & Hooey, 1997; Casali, 1986; Frank, Casali, & Wierwille, 1988). Many of today's driving simulators are used to perform research, training, or design evaluation. A prerequisite to generalizing the results found in research conducted in a simulator is an understanding of the validity of the resulting experience (see Ranney, this book, chap. 9). Without question, simulator sickness can undermine the validity of simulator data. Simulator sickness can affect an operator's performance (Uliano, Lambert, Kennedy, & Sheppard, 1986), although it need not always do so (Warner, Serfoss, Baruch, & Hubbard, 1993). Simulator sickness affects performance in a variety of different ways including the execution of inappropriate behaviors, loss of motivation (often including cessation), inability to concentrate (Kennedy et al., 1987), avoidance of tasks that are found disturbing, modification of behaviors to reduce symptoms (Silverman & Slaughter, 1995), distraction from normal attention allocation processes (e.g., closing eyes during turns, Silverman & Slaughter), and a pre-occupation with the fact that something is not quite right. Given the potential consequences of simulator sickness, it is difficult to assess the generalizability of the results obtained from a simulator if sickness is not carefully monitored and managed.

In addition to problems with validity created by simulator sickness, there is potential danger to the participants both during and long after an experiment has been completed. As one might expect, the effects of simulator sickness on participants' performances are most likely to occur in initial exposures to a simulator, particularly when there are high rates of optic flow and frequent changes in acceleration (Hettinger & Riccio, 1992). This creates a huge challenge for creators of driving simulation systems where such factors are necessary component of the simulated task.

Additionally, due to lingering reactions, there can be effects on participants using a driving simulator long after the simulation experience. Blurred vision, postural instability, nausea, and general discomfort are the types of lingering symptoms that can be experienced (Johnson, 2005). Flight simulators, particularly those used for training high-g maneuvers, are more likely to produce long-term after-effects. Even for these simulators, only 4.6% of Navy pilots suffered from symptoms 24 hours or more after simulator-based training (Ungs, 1989). Kennedy, Fowlkes and Lilienthal (1993) conclude that the most dangerous potential after-effects are disturbances in locomotor and postural control. These effects can last for hours, or potentially much longer. This can occur in high-g simulators but extended effects have been reported on other simulators as well. For example, when exposed to long periods of rotation, usually not a problem in most simulators, effects have been measurable three or four days after exposure (Fregly & Kennedy, 1965). Even longer-lasting effects have been reported (Berbaum, Kennedy, Welch, & Brannan, 1985; Guedry, 1965; Goodenough & Tinker, 1931). Care must be taken by simulation users to understand the impact of simulation exposure on the participant and protect him or her from potential danger.

Given its impact on a researcher's ability to undertake and complete an experiment, and on a practitioner's ability to undertake and complete training programs, simulator sickness has been widely researched and is the subject of a number of comprehensive reviews, most often for military applications (e.g., Crowley & Gower, 1988; Goldberg & Hiller, 1995; Johnson, 2005). We cannot hope to cover the breadth and depth of the work that has been done. However, we will do our best to introduce the reader to the extensive literature on the topic. To begin, it is important to understand the underlying mechanisms and processes that cause simulator sickness. A thorough understanding should allow for better design of scenarios, techniques for tuning the simulator, and novel experimental techniques to help reduce simulator sickness. The following section provides a brief explanation of the theoretical basis that explains the role of the visual and vestibular systems in simulator sickness and the physiological mechanisms associated with simulator sickness. A discussion follows of different possible measures of simulator sickness and then the methods one can use to prevent such sickness.

14.2 Theories of Simulator Sickness

There are several theories behind the concept of simulator sickness. The three most prominent theories are: cue conflict theory, poison theory, and postural instability. More recently, it has been hypothesized that it is not a conflict in the cues per se that is responsible for simulator sickness, but rather a conflict in the rest-frames that correspond to those cues. This theory will also be discussed because it suggests a range of actions that might be taken to mitigate simulator sickness.

14.2.1 Cue Conflict Theory

Cue conflict theory is the primary theory used to describe the etiological processes that occur with simulator sickness (Reason & Brand, 1975). (The reader is also referred to chap. 8, "Sensory and Perceptual Factors in the Design of Driving Simulation Displays," by Andersen in this book.) The main premise of the theory is that sickness occurs due to mismatches between what the sensory systems expect based on previous experience and what actually occurs in the simulator. The mismatch causes internal conflict that cannot be resolved and eventually results in the symptoms associated with simulator sickness. An example of this conflict can be found in a fixed-base simulator where visual cues are presented to indicate linear acceleration but because the driver is not actually moving, no corroborating or correlated vestibular cues are detected. Drivers of real vehicles have learned to expect that with visual cues of acceleration there will also be a corresponding vestibular cue of acceleration. Therefore, a conflict will be detected and simulator sickness could result. Examples also occur in motion-base and head-mounted simulators as well. For example, in a motion-base simulator where both visual and vestibular cues are delivered, there may be too long between an onset in the motion or visual cues. And in a head-mounted display (fixed-base), the vestibular cues delivered by head movements may not correspond to the actual changes in the visual world displayed to the participant which are naturally produced by such head movements.

There are a number of types of cue mismatch that can lead to cue conflict in driving simulators. To begin with, there are two broad categories of conflict: intermodal (e.g., conflict between the cues given by the vestibular and visual systems) and intramodal (e.g., conflicts between the cues given by the semicircular canals and the cues given by the otolith organs within the vestibular apparatus; Griffin, 1990). Additionally, within each category, there are three types of conflict that could occur: 1) signals exist from two separate cueing systems, say A and B, and they provide contradictory information; 2) signals are present from A, but not from B; and 3) signals are available from B but not from A.

Perhaps the most salient conflict is the conflict between the intermodal cues generated by the visual system and the vestibular systems. The coupling between these is quite close given their importance to spatial orientation and the rapid exchange of information that is required to support balance and locomotion. Examples can be generated for each of the three types of conflict that could occur between the visual and vestibular systems. 1) Conflict would exist between the visual and vestibular system cues if a display was head-mounted and the signal from the head-mounted display were either noisy or inaccurate. 2) Signals from the visual system could be present, but those from the vestibular system absent, in a fixed-base simulator. In particular, these two systems provide potentially different information when the speed is changing or the vehicle is turning. 3) Finally, in a head-mounted system, signals from the vestibular system would be present, but those from the visual system absent, if a low display update rate were used. Other conflicts will be discussed below.

There does appear to be a relationship between the level of experience an individual has performing a real-world task outside of a simulator and the incidence of sickness seen while performing the task in a simulator (Pausch et al., 1992). The more experience an operator has, the more likely that he or she is to experience symptoms. This supports cue conflict theory in that the more intimate the operator is with the types of sensory responses he or she should be receiving, the more likely he or she will be to either consciously or unconsciously recognize when something does not match.

An important finding in motion sickness research is that a necessary requirement for experiencing sickness is a working vestibular system (McCauley & Sharkey, 1992, reviewing Howard, 1986). Such a finding is certainly consistent with cue conflict theory since there can be no conflicts between the visual and vestibular systems. Even though cue conflict theory is the most widely accepted theory of simulator sickness, there are several problems with it that have led some to question its utility as an explanation for simulator sickness (Stoffregren & Riccio, 1991). The first issue is that the theory does not allow for effective prediction of simulator sickness. There is no reliable formula based on sensory inputs and conflicts that can be used to determine which situations will produce sickness and which will not (Draper et al., 2001; Stoffregen & Riccio, 1991). This has led some investigators to conclude that in its present form the theory may be untestable (Ebenholtz, Cohen, & Linder, 1994, p. 1034). Second, according to the theory, lack of cue redundancy—such as either no motion or inadequate motion as reported by the vestibular system and motion reported by the visual system—is a major determinant of when sickness will occur. However, there are many environments where sensory cueing is not redundant which do not produce sickness. For example, no redundancies are present when an individual is sitting in a room watching a chase video. Yet, individuals do not experience sickness in such environments. Therefore, having no-motion or inadequate motion is not a clear predictor of simulator sickness rates. Third, there is no explanation for why simulator sickness is prevalent at first exposures and then will tend to disappear after repeated exposure. Last, there has been no physiological explanation of why cue conflict will result in a nauseogenic response. There are no known neural processing centers that would account for such a response and it is unlikely that there is an undiscovered neural processing center that is dedicated to this particular response.

Even with its potential drawbacks, available experimental data do tend to support the cue conflict theory fairly well and it remains the most widely accepted view. In terms of experimental design, scenarios which reduce cue conflict between the vestibular and visual systems, either by attenuating the expected inputs from the vestibular system (i.e., scenarios with few sharp turning movements or low calculated acceleration forces) or attenuating the optic flow in the visual system (i.e., scenarios which maintain an adequate distance from landscape features such as trees and signs and scenes which contain relatively few elements), will result in a lower sickness rate.

14.2.2 Poison Theory

The poison theory attempts to explain simulator sickness from an evolutionary point of view (Treisman, 1977). With this theory, it is believed that the types of sensory stimulation artifacts found in virtual environments such as blurred vision, temporal instability, and lack of sensory coordination caused by low visual resolution and improper or scaled motion cueing, are similar to the symptoms one experiences as a result of poison or intoxication. One of the body's most automatic responses to poison is vomiting in order to empty the contents of the stomach. There the premise of this theory is that the effects of virtual environments lead the body to believe that it has ingested poison and the body reacts to rid itself of the problem. As with the cue conflict theory, there are also problems with the poison theory. There is no way to predict when or how fast individuals will elicit an emetic response and thus there are no obvious recommendations for mitigating simulator sickness that derive from the theory. There is also no explanation as to why some individuals, such as pregnant women, are affected more than others, especially in the case of experience with the real-world task. Due to these limitations, it is hard to evaluate this theory. However, this theory could easily be layered on top of cue conflict theory to explain the nauseogenic response.

14.2.3 Postural Instability

The postural instability theory of simulator sickness was developed as an ecological alternative to cue conflict theory. The theory is centered on a premise that the sensory systems are constantly attempting to maintain postural stability in our environment. Postural stability is a state where uncontrolled movements attempting to correct perceived variance from normal postural states are minimized (Riccio & Stoffgren, 1991). So our perceptual and action systems are continually attempting to maintain our postural stability in our environment. Sickness occurs when an individual is attempting to maintain stability under a set of new environmental conditions when they have not yet learned strategies for accomplishing the task. The key to this statement is the new environment. Experienced drivers may become sick in a simulator because it is a new environment where they are trying to apply the skills acquired on the road. This may be best typified by passengers more likely to become sick than drivers in both simulators and actual driving situations (Rolnick & Lubow, 1991). These same phenomena have been observed for small aircraft.

In support of this theory, Stoffregen and Riccio argue that postural instability not only precedes sickness (Stoffregen & Riccio, 1991) but is also necessary to produce symptoms. They also note that in both vehicles and laboratory whole body motion platforms, motion sickness is most likely to occur when periodic motion is imposed at frequencies between 0.08 Hz and 0.4 Hz, which is similar to the range of frequencies that characterize walking. The interaction of the imposed oscillations with the body's natural oscillations could lead to wave interference and the resulting severe disturbances. Although there is no explanation for how the lack of postural stability ultimately results in an emetic response, the theory does provide some basis for the diminishing effects of sickness as the individual learns the environment. And it would be consistent with efforts to expose individuals more gradually over time to a driving simulator in order to reduce symptoms to a minimum. Finally, because postural instability precedes simulator sickness, it could be used as a way to predict and potentially reduce such sickness (also see later discussion).

14.2.4 Rest-Frame Hypothesis

Recently, Prothero, Draper, Furness, Parker and Wells (1999) presented evidence that suggested that it was the conflict between the rest-frames implied by the constellation of visual cues available to an individual—and not the cues themselves—that was creating much of the observed simulator sickness. So, for example, if the participant is sitting in a fixed-base, visually-immersive simulator, then the rest-frame defined by the elements is the room itself (if the chair in the room upon which the driver is sitting is at rest, the driver is at rest); whereas the rest-frame defined by the displays on the screen is the virtual world (if the participant is moving through the virtual world, the participant is in motion). The rest-frame is the particular reference frame which an observer takes to be stationary, largely to reduce calculations of relative motion (Prothero, 1998). It seems as if these two are inevitably in conflict with a fixed-base simulator. However, interestingly, Prothero et al. (1999) argued that the virtual environment could be parsed into two elements—the content and the independent visual background (IVB) upon which that content is displayed. If the rest-frames implied by the IVB and the inertial frame of the participant (the room) could be linked, then this should reduce the conflict between the visual and vestibular cues since the rest-frames are aligned.

To test their hypothesis, Prothero et al. (1999) asked participants to wear a head-mounted display while standing. Measures were taken of postural disturbance and simulator sickness. In the semi-transparent mode, the participants could see the laboratory wall behind them through the lenses of the display. In the opaque mode, they had no independent visual background. Prothero et al. reported less postural disturbance and simulator sickness when the IVB was visible. Duh, Parker and Vanesse (2001) extended the results of Prothero et al. Again participants were standing; this time, however, the display was presented on a screen and the independent visual background was a simple grid superimposed over the display. There were three grid conditions: bright, dim and none. Again, the IVB reduced postural disturbance which is known to be associated with simulator sickness. Finally, an interesting extension of this into the arena of driving simulation was recently made by Lin, Abi-Rached, Kim, Parker, & Furness, (2002). Briefly, they asked participants sitting in the passenger seat in a driving simulator to report levels of sickness and enjoyment in one of four conditions: (1) no avatar, (2) an earth-fixed visually-guided avatar (a plane hovering in the sky), (3) an earth-fixed visually-guided avatar which indicated to the passenger in which direction the car would turn, and (4) a non-earth-fixed visually-guided avatar which again indicated turning directions. In the second and third conditions, the participant had independent information about the visual background. There were decreases in sickness in both conditions, but they were not statistically significant in the second condition (which provided an IVB, but no prediction about where the car would be turning). It is not clear, however, whether an IVB such as a visually-guided avatar, would actually help the driver (as opposed to a passenger) in a fixed-base simulator.

Although none of the competing theories fully explain the simulator sickness phenomenon, we can take a conservative approach to simulation design by working to create an environment, simulator, scenes and scenarios which will, within the context of each theory, reduce simulator sickness. Below, we look specifically to the visual and vestibular systems as areas that are both the primary causes of simulator sickness and the source of possible remedies.

14.3 The Visual Systems

In this section, the focus is on the visual systems, the potential such systems have for producing cue conflict, and the steps one can take to reduce such conflict. As noted above, other theories have been used to explain the existence of simulator sickness. Where obviously relevant, these theories will be introduced as well.

The visual system is a very complex and heavily researched sensory system. It is not within the scope of this chapter to provide a full description of the anatomy and processing that make up visual perception. Other reference materials such as Goldstein (1989) provide good explanations of the visual system. Within the scope of this chapter, it is important to understand key characteristics of the visual system that have some influence on the development of simulator sickness.

14.3.1 Central Versus Peripheral Vision

As our eyes move to acquire a target and then process it, they are working to focus the target image on the retina within the area of the fovea. The resulting area of perceived vision has been referred to as central vision. The receptors responsible for central vision are good at maintaining a sustained response which means they will continue to fire as long as the stimulus is present. Because the image must often be stabilized for some period of time while the perceptual processing occurs (e.g., when then head is moving, or the entire individual is moving), movements of the eye exist to support this stabilization including saccades, smooth pursuit, the vestibule-ocular reflex (VOR), and the optokinetic reflex (OKR). Of these eye movements, VOR and OKR are of particular interest when considering the effects of virtual environments and resulting simulator sickness; and they will be discussed later in further detail.

The area surrounding the fovea is not well adapted for seeing specific targets but is good at detecting moving objects and plays a central role in the perception of self-motion. The perceived vision from this area is called peripheral vision (Leibowitz, 1986). The receptors outside the fovea are much better suited for detecting transient stimuli and will fire as they detect a stimulus but will not continue to fire. Therefore, the peripheral sensors are sensitive to moving objects and also changes in orientation of the individual. Information about changes in orientation is believed to feed back into the part of the brain that determines posture, balance, and self-motion, acting almost as a proprioceptive sense. Information about changes in the location of objects in peripheral vision over time provides information about how an observer is moving through his or her environment. Movements of an observer through the real world (or of a virtual world around an observer) are coded by peripheral vision as optic flow.

14.3.2 Optic Flow

Here we talk about the contribution of optic flow to simulator sickness. To repeat, optic flow is created by the movement of elements in the optic array that occur as an observer moves relative to his or her environment (Goldstein, 1989). A simple example of this can be found as you ride in a vehicle and you fix your gaze in the direction you are traveling. All objects within the field of view will appear to move away from the center of your destination or point of expansion (POE). Figure 14.1 illustrates the directions that objects will appear to move as you move through the environment.

Optic flow provides information relevant to steering and turning. Optic flow also provides information about our speed relative to the environment. The more rapidly objects move along the flow lines, the faster the observer perceives their motion. Thus, immersive display devices and screens that display an image to the side as well as to the front and both well above and below the POE will emphasize the optic flow and, consequently, will contribute to the conflict between the visual and vestibular systems and simulation sickness. Human perception of changes in optic flow appears to be quite sensitive and often occurs without conscious thought or effort. Optic flow that specifies movements that do not coincide with vestibular cues can produce sensory conflict which can induce simulator sickness. Consequently, one way to reduce simulator sickness is to reduce optic flow, which can be achieved by decreasing the field of view and by removing elements in a scene that contribute to optic flow.

14.3.3. Perceived Self-Motion

Optic flow also contributes to perceptions of self-motion (much of the following description of perception of self-motion is taken from LaViola, 2000). Under various circumstances, individuals that are static with respect to their environment may experience a compelling illusion of self-motion. This effect is known as vection. Vection is typically measured by asking subjects to rate its magnitude (Prothero, 1998). Vection can occur in naturalistic environments such as looking out the window of a vehicle and feeling motion due to the movement of an adjacent vehicle even though no self-motion is present. These effects have often been seen in virtual environments as well. "Immersive" virtual

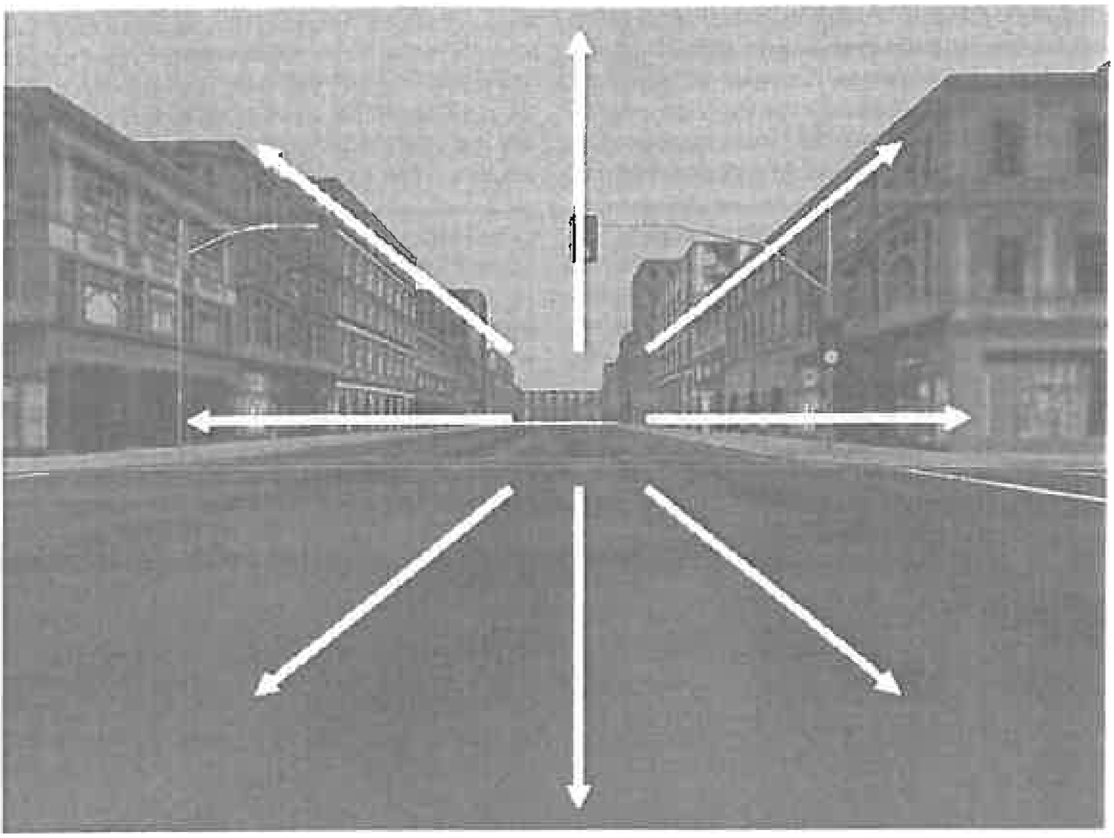

FIGURE 14.1 Optic flow example.

environments with wide field of view displays or helmet-mounted displays where fewer references to a static world exist are prone to causing this effect. In the case of a fixed-base simulator, these effects are being generated by changes in the optic flow.

The strength of vection can be influenced by several factors. Larger fields of view (greater than 30 degrees) have been shown to produce greater perception of motion. This is likely due to the increased information provided in the peripheral field of view which has been shown to have a greater influence on perception of self-motion (Johnson, 2005). Wider fields of view are often found in modern driving simulators because there are many instances in driving where full left and right scanning is required to negotiate the environment. Intersections are a good example where you must be able to look 90 degrees left and 90 degrees right in order to check for traffic, pedestrians, etc., before proceeding. Thus, it can be difficult to reduce the field of view and the resulting experience of vection while still maintaining scenarios that can test one's hypotheses.

Also important to the experience of vection is the rate of optic flow where increased flow rates equate to greater perception of speed of vection. Unlike an aircraft simulator, a typical driving scene has a high rate of optic flow because the observer's eye point is close to the road surface (low altitude). In addition, there are typically many more features in the scene that are close to the driver such as other vehicles, buildings, signs, roadside vegetation, etc. Measures can be taken in the design of a scene to reduce the elements that contribute to vection without necessarily compromising the validity of the study. For example, one could easily replace a picket fence along the side of the road with a rail fence.

As noted above, the changes in optic flow provided by the visual system provide both translational and rotational information. In a standard environment, these changes in optic flow would be accompanied by corresponding vestibular information. However, in a virtual environment, the vestibular information is not available for inter-sensory corroboration. As noted above, it is the result of this effect that forms the basis for the sensory conflict theory of motion sickness. However, it should be made clear the sensory conflict exists even without the perception of self-motion. The conflict may be enhanced if the participant also feels like he or she was in motion, but it is not known whether this is the case. In either case, factors that reduce vection reduce optic flow and therefore, presumably, cue conflict.

14.3.4 Perception of Depth

Our perception of depth comes from a number of sources including oculomotor cues, pictorial cues, motion-produced cues, and binocular disparity. The oculomotor cues are those given by the position of our eye and tension on the muscles within the eye. Pictorial cues are those that could be extracted from a still picture. Motion-produced cues depend on the motion of the observer or the objects in the environment. Binocular cues come from the fact that slightly different scenes are formed on the retina of our eyes. Oculomotor and motion produced cues are the only two sources of information likely to produce cue conflict.

The oculomotor cues include convergence and accommodation. Both operate by giving proprioceptive feedback to the brain about where an object is located upon which an observer is focusing. Convergence is the inward angular positioning of the eyes to keep an object focused on the fovea as the object is moved closer to the observer. The closer the object is to the observer, the greater is the muscular input required to keep it positioned on the fovea. Accommodation is the process of flexing muscles in the eye to change the shape of the lens as an image is brought into clear focus on the retina. The closer the object, the more muscle tension is required to bulge the lens of the eye. These effects typically only occur when the target object is within a distance of 5–10 feet. Objects further away are normally focused without any adjustments to the orientation of the eyes. Thus, there is the potential for cue conflict between the kinesthetic and visual systems when the display is located more than 5–10 feet from the driver since the oculomotor cues (convergence and accommodation) are not present, but the visual cues are present, as the driver focuses on an approaching vehicle.

Motion-produced depth cues include motion parallax and accretion and deletion. As an observer moves through an environment, objects that are further away appear to move slowly in the direction of the observer's movement. Closer objects appear to move more rapidly in the direction opposite the observer's movement. The apparent angular velocities of the objects will be inversely proportional to their distance from the observer. Accretion and deletion are related to motion parallax and interposition. If two surfaces are at different distances from the observer, any movement in the observer that causes one surface to cover another will give cues to depth. The covering surface is seen to be closer then the covered surface. In fixed- and motion-base simulators, motion-produced cues such as parallax are well reproduced when the vehicle's direction changes heading, but not when the driver himself or herself moves around in the cabin, leading to potential for cue conflict. In head-mounted simulators, these intramodal cue conflicts are not present.

14.3.5 Optokinetic Reflex

The optokinetic reflex (OKR) is one of several eye movements that function to identify a target in a visual scene, to position the target on the fovea, and to keep it positioned there. The OKR works by evaluating information from the entire retina to determine if image slip is occurring (e.g., the target is moving with respect to a fixed observer). If there is an image slip, a corresponding movement is made in the eye position to eliminate it, thus stabilizing the image. An example of this process at work is when we look out the window of a vehicle (assuming the head is still; otherwise with the head in motion the vestibulo-ocular reflex is also at work; see discussion below). As the optokinetic reflex detects slippage in the image, it applies a compensating movement to the eye with a gain equal to the motion and direction of the optic flow. The small differences between the eye and the image generator of the simulator can be at odds with each other. The human eye does not process information in a discrete number of frames per second, but the image generator in a simulator does. Whether the OKR adjusts perfectly for the stepwise slip of a digitally projected moving image is not clear; but if it does not, there will be intramodal conflicts between what the eye perceives and what it expects to perceive based on the faulty adjustment applied by the optokinetic reflex. Arguably, the validity of the OKR adjustment will improve as the frame rate increases.

14.4 Vestibular Systems

There are both central and peripheral vestibular systems. It is the peripheral vestibular system which interests us the most. Specifically, we focus on the potential such systems have for producing cue conflict, and the steps one can take to reduce such conflict. The peripheral vestibular system rests in an area of the inner ear called the labyrinth. It is made of up a series of tubes (semicircular canals) and sacs (utricle and saccule). The semicircular canals are primarily responsible for detecting angular acceleration in each of the three planes in which motion can occur. They are quite sensitive and can measure angular accelerations as low as 0.1 deg/s^2 (Gianna, Heimbrand, & Gresty, 1996). The utricle and saccule are responsible for detecting linear acceleration. The utricle is oriented to be able to detect motion in the horizontal plane; the saccule is oriented to detect motion in the vertical plane and fore-aft plane. Once the brain receives the impulses from the entire vestibular system, it uses the information for perception of motion and also transmits information to the visual system. More discussion of this process will be included in the following sections.

14.4.1 Vestibulo-Ocular Reflex

There is a clear relationship between the vestibular and visual systems where angular acceleration information about head movement is supplied to the visual system. The visual system interprets this information and makes a corresponding eye movement to stabilize the visual image on the retina. The process is called vestibulo-ocular reflex (VOR). A simple example of this effect can be shown by holding a piece of paper with some printed text in front of your eyes. If you move your head while holding the paper stationary, you will be able to read the text with some level of effort. If you hold your head stationary and move the paper, it is much more difficult or perhaps even impossible to read the text. When the head moves, the vestibular system is providing information to the eyes allowing them to stabilize the image of the shaking paper on the retina. In the case where the paper was moving, there was no information about how the paper was moving that could be sent to the eye and so the image could not be stabilized.

14.4.2 Vestibulo-Ocular and Optokinetic Relfexes

Often, both the head and the image are moving. In this case, the vestibular-ocular reflex (VOR) and the optokinetic reflex (OKR, as discussed earlier) work together synergistically to maintain a stable retinal image regardless of the type of motion being experienced (Zacharias & Young, 1981). The VOR is a very fast-acting reflex which serves to compensate for head movements in the 1–7 Hz range. However, the VOR is much less accurate at lower frequencies and has less than perfect gain. The OKR has the opposite performance characteristics. It has a longer latency due to the required evaluation of visual information to determine a response and has near unity gain at low (<0.1 Hz) frequencies. Between 0.1 and 1.0 Hz frequencies, the OKR begins to lose gain and also develops a phase lag due to inherent response latency. The two reflexes working in unison are able to provide stable retinal images through a wide range of frequencies. Cue conflict occurs primarily with head-mounted displays (Draper, 1996). Although not so true with today's head-mounted displays, slow sensors and/or slow scene rendering will create a mismatch between what it is expected to be seen (based on the VOR and OKR synergies) and what is actually seen (based on what is displayed).

14.4.3 VOR Adaptation

It has been demonstrated that the VOR response is adaptable, in that gain values will be adjusted to accommodate different sensory arrangements. An example is provided by the case of looking through magnified optics such as scuba goggles. VOR will adapt its gain to match the amount of eye movement required to stabilize the image even under the modified conditions. In a study to evaluate the effects of visual scale factor on VOR, Draper (1998) found that visual magnifications of 2× and 0.5× did result in corresponding VOR adaptations and that the visual adaptation was correlated with simulator sickness. One explanation is that OKR provides a tight feedback loop of information to the VOR adaptation process, allowing it to tune itself to the given conditions. VOR adaptation, or speed of VOR adaptation, has been hypothesized to be a predictor of simulator sickness potential where individuals who adapt faster are less likely to experience sickness symptoms (Draper et al., 1997). This link might explain how subtle artifacts of poor simulator engineering might delay the VOR adaptation process either through inconsistent feedback or by altering the performance of the OKR through visual anomalies.

14.5 Measures of Simulator Sickness

There are a number of different measures of simulator sickness that have been used. Below, we discuss several, including the most common subjective rating scale, as well as several alternatives, including postural stability and physiological measures. Additionally, we discuss the issue of when to measure just how sick a simulator makes an individual during a particular session and whether to use indices of simulator sickness as a covariate in measures of performance.

14.5.1 Simulator Sickness Questionnaire

The Simulator Sickness Questionnaire (SSQ) developed by Kennedy, Lane, Berbaum, and Lilienthal (1993) is perhaps the most widely used instrument, cited in over 300 publications since it first appeared. It is derived from the Pensacola Motion Sickness Questionnaire (MSQ) developed some 30 years previously (Kennedy & Graybiel, 1965). The MSQ had a total of 28 different symptoms that were evaluated by participants. The SSQ was developed from the pre- and post-test assessments of motion sickness using the MSQ. A total of 1,119 pre- and post-test pairs from the MSQ were evaluated, the pairs collected on 10 different simulators. Because the goal was to determine which symptoms showed changes from pre- to post-test, those symptoms were excluded that showed little change. For example, vomiting was experienced in less than 1% of participants and was therefore excluded. Additionally, signs that were observed on only some simulators and appeared irrelevant to simulator sickness were excluded, e.g., boredom. A final set of 16 symptoms was included. They are listed in Table 14.1.

In order to determine whether there were sets of symptoms in the SSQ which were correlated with each other, a principal factors analysis was performed. Three subscales were identified, one related to nausea (N in Table 14.2), one related to oculomotor problems (O), and one related to disorientation (D). If, in the factor analysis, the loading on a factor of a given symptom was greater than 0.30, the symptom was included in the *total factor score* (marked as a 1 in the appropriate column in Table 14.2); otherwise it was not included. The total score on each factor could then be computed. It was equal to the weighted sum of the symptom scores for a factor. The symptom score was 0, 1, 2 or 3 as rated by an individual participant (Table 14.1). So, for

TABLE 14.1 Simulator Sickness Questionnaire

Directions: Circle one option for each symptom to indicate whether that symptom applies to you *right now*.

1.	General Discomfort	None	Slight	Moderate	Severe
2.	Fatigue	None	Slight	Moderate	Severe
3.	Headache	None	Slight	Moderate	Severe
4.	Eye Strain	None	Slight	Moderate	Severe
5.	Difficulty Focusing	None	Slight	Moderate	Severe
6.	Salivation Increased	None	Slight	Moderate	Severe
7.	Sweating	None	Slight	Moderate	Severe
8.	Nausea	None	Slight	Moderate	Severe
9.	Difficulty Concentrating	None	Slight	Moderate	Severe
10.	"Fullness of the Head"	None	Slight	Moderate	Severe
11.	Blurred Vision	None	Slight	Moderate	Severe
12.	Dizziness with Eyes Open	None	Slight	Moderate	Severe
13.	Dizziness with Eyes Closed	None	Slight	Moderate	Severe
14.	Vertigo[a]	None	Slight	Moderate	Severe
15.	Stomach Awareness[b]	None	Slight	Moderate	Severe
16.	Burping	None	Slight	Moderate	Severe

Source: R. S. Kennedy, N. E. Lane, K. S. Berbaum, & M. G. Lilienthal., Simulator sickness questionnaire: An enhanced method for quantifying simulator sickness. *International Journal of Aviation Psychology,* 3(3):203–220, 1993. With permission.

[a] Vertigo is experienced as loss of orientation with respect to vertical upright;

[b] Stomach awareness is usually used to indicate a feeling of discomfort which is just short of nausea.

TABLE 14.2 Simulator Sickness Questionnaire

	Weight		
SSQ Symptoms			
General Discomfort	1	1	
Fatigue		1	
Headache		1	
Eye Strain		1	
Difficulty Focusing		1	1
Increased Salivation	1		
Sweating	1		
Nausea	1		
Difficulty Concentrating	1	1	
Fullness of Head			1
Blurred Vision		1	1
Dizzy (eyes open)			1
Dizzy (eyes closed)			1
Vertigo			1
Stomach Awareness	1		
Burping	1		

Source: R. S. Kennedy, N. E. Lane, K. S. Berbaum, & M. G. Lilienthal., Simulator sickness questionnaire: an enhanced method for quantifying simulator sickness. *International Journal of Aviation Psychology,* 3(3):203–220, 1993. With permission.

example, if a participant rated the seven symptoms under nausea as, respectively, 3, 2, 1, 2, 3, 2, 1 the unweighted nausea factor score would be 14. The weighted nausea score (N_s) would be 14 × 9.54. The weights for O and D were, respectively, 7.58 and 13.92. The *total score* was equal to the sum $N_s + O_s + D_s \times 3.74$.

14.5.2 Times of Administration

A potential problem with self-rating measures of simulator sickness has recently been addressed. In particular, participants, alerted to the possibility of simulator sickness in a pre-questionnaire (or other instructions) may thereby experience more simulator sickness than would someone not informed. In order to test this hypothesis, 30 participants between the ages of 20 and 45 years old were given the SSQ, either before and after exposure to a virtual environment, or just after exposure to that environment (Young, Adelstein, & Ellis, 2007). A head-mounted display was used. The average post-test SSQ (11.0) score of participants administered both the pre-test and post-test was roughly 80% higher than the post-test score (6.0) of participants administered just the post test, a difference which was statistically significant. The authors note that it is not clear whether the participants actually experienced more simulator sickness in the group that was administered both a pre-test and post-test or simply reported more simulator sickness at the end. This is certainly something that should be addressed in future research. The use of postural and physiological measures such as those discussed below could answer this question. Nevertheless, it is clear that comparisons of SSQ scores across experiments must take into account what was told to the participants prior to exposure.

14.5.3 Postural Stability

As noted previously, postural instability theory was proposed as an ecological alternative to cue conflict theory (Riccio & Stoffregen, 1991). It follows that measures of postural instability might be used to predict motion and simulator sickness. Towards this end, Soffregen and Smart (1998) exposed standing participants to the very small oscillatory motions that are typical of walking, using a moving room (Stoffregen, 1985). Symptoms of simulator sickness were preceded by changes in postural sway, measured here as changes in the variability, velocity and range of head movements.

The above results are not strictly applicable to a virtual environment. Thus, Stoffregen, Hettinger, Haas, Roe and Smart (2000) used a fixed-base flight simulator to determine whether indices of postural sway preceded symptoms of simulator sickness in a virtual environment. The outside world was projected on a dome. The star field and a spacecraft projected on the star field oscillated in the roll axis on the experimental trials and remained constant on the control trials. Each participant was in the simulator for approximately two hours. The SSQ (long and short forms) was administered before testing, immediately after testing on the nauseogenic stimuli (sum-of-sines scenarios), and then one hour post-test. Head movement was measured throughout the testing using a magnetic tracking device. A total of 14 participants were run in the experiment. Six became sick; eight did not, as measured by the SSQ and the experimenters.

Prior to the testing, there were a number of differences in postural motion in the sick and well groups. For example, there were significant differences in the velocity of head movements in the yaw and roll axes. In each case velocity was greater in the sick group. Interestingly, it is estimated that these two measures accounted for roughly one-third of the variance, more than can currently be accounted for by physiological variables (Kennedy, Dunlap, & Fowlkes, 1990). Perhaps more importantly, postural motion predicted sickness not only for the strongly nauseogenic stimuli (the sum-of-sines scenarios), as indicated by significant increases in head velocity in those who later became sick, but also for the less nauseogenic stimuli (the 0.2 Hz oscillation). This prediction was made during the first 10 minutes of the experiment (Trial 5, a sum-of-sines trial). Note that the predictors of simulator sickness in this experiment (velocity of postural motion) were not the same as the predictors of motion sickness in an earlier experiment (variability of postural motion; Stoffregen & Smart, 1998). Kennedy et al. (1993) argue that this is not problematic for the postural instability theory (Riccio & Stoffregen, 1991) because no one parameter enjoys dominance in the theory. Practically, this means that investigators would need to measure variability, velocity and range of postural motion in all six degrees of freedom.

14.5.4 Physiological Measures

Physiological measures have not received the attention one might have expected given their clear relation to the symptoms of simulator sickness. Perhaps this is because very few clear relationships have emerged in most prior studies (Biaggioni, Costa,

& Kaufmann,1998; Bolton, Wardman, & Macefield, 2004; Collet, Vernet-Maury, Miniconi, Chanel, & Dittmar, 2000; Espié, 1999; Gianaros et al., 2003; Mullen, Berger, Oman, & Cohen, 1998). However, two recent studies seem to suggest that there may indeed be a relation (Bertin et al., 2004; Min, Chung, Min, & Sakamoto, 2004). We will focus here on one such study (Bertin et al., 2004).

In that study, drivers sat in an actual car. The virtual world was presented on three large screens subtending 150 degrees of visual angle. The continuous physiological data recorded included skin potential (SP), skin resistance (SR), skin temperature (ST) and heart frequency (HF). A continuous psychophysical measure of simulator sickness was also recorded by asking participants to indicate their condition by moving a cursor along a visual analog scale containing 10 stops, anchored at one end by "all is fine" and at the other end by "I'm about to vomit". The participant could control the movement of the cursor using levers on the steering column. The visual analog scale was projected low in the visual field. Strong reliable correlations were reported between simulator sickness scores and three of the four physiological variables (SR, ST and HF). It is not clear why some studies, such as this one, find such strong correlations. One possibility is that simulator sickness is a constellation of factors, as reflected in the three dimensions that underlie the SSQ. Clearly, it would be useful to better understand what controls the strength of the correlations, because physiological indicators could provide a very valuable tool in managing simulator sickness.

14.5.5 Use as a Covariate

Simulator sickness presents several challenges in the process of data collection and interpretation. Most obvious among the challenges is the discomfort and distress it can cause participants. It can also lead to lost data when a participant withdraws from a study before completing the experiment. Such lost data can jeopardize the integrity of the analysis because it might affect some experimental conditions more than others and some populations of participants more than others.

A more subtle effect concerns the situation in which a participant does not withdraw from the study, but drives differently as a result of feeling ill. Drivers might behave differently to minimize the cues that are causing the ill feelings, such as closing one's eyes when negotiating a turn. Feeling ill can also pose a distraction that might have more diffuse effects. Obviously the ideal approach is to design the simulators, scenarios, and protocols to avoid simulator sickness. Another is to statistically assess the influence of simulator sickness by using the SSQ or other measures as a covariate in an ANCOVA. Such an analysis identifies the potential confounding effect of simulator sickness and offers the potential of adjusting for its effect (Bittner et al., 1997).

14.6 Factors Associated With Simulator Sickness: Preventive Measures

The factors associated with simulator sickness can neatly be divided into simulator, task, and individual characteristics. There is much that can be done to alter the simulator and task characteristics. These measures include the simulator hardware itself, the scenes and scenarios that the participant needs to negotiate, the environment within which the simulator is located, the monitoring of ongoing levels of simulator sickness, and the careful adaptation of a driver to the simulator environment. A number of authors have published guidelines to reduce simulator sickness (Braithwaite & Braithwaite, 1990; Crowley & Gower, 1988; Kennedy et al., 1987; Kolasinski, 1995; Lilienthal, Kennedy, Berbaum, Dunlap, & Mulligan, 1987; McCauley, 1984; Naval Training Systems Center, 1988; Wright, 1995). Arguably the most thorough set of guidelines are those by Kennedy et al. and Wright. The reader may find additional suggestions in these guidelines specific to his or her particular situation. Although there is little if anything that can be done to alter the individual differences prior to an experiment (beyond screening high risk participants), exposing especially high risk individuals to a virtual environment in a slow, stepwise fashion is always possible as a way of potentially decreasing such individuals' risk (Johnson, 2005).

14.6.1 Simulator Design Factors

We have talked about some of the factors due to the design and construction of a simulator that impact simulator sickness. Below, we give a more complete list of these factors, including the type of simulator, field of view, display alignment, image resolution, graphics update and refresh rates, motion system, calibration of eye height, and transport delay. It goes without saying that a simulator whose fidelity matched that of the real world is the gold standard. Even with such a simulator, motion sickness could still be a problem, just as it is for some drivers on some roads; however, no existing simulator can do this. Moreover, what at first seems like a higher fidelity simulator can sometimes perversely increase simulator sickness. The best example is the addition of a motion base. Clearly, a simulator with motion has the potential to be of higher fidelity than a simulator without motion. But, if the visual and motion cues are still in conflict, then nothing is gained and poorly correlated motion could confront drivers with a greater perceptual mismatch than no motion. Regardless, there are still things that the researcher can do.

14.6.1.1 Types of Simulators

Prior to purchase, a researcher needs to decide whether to get a fixed-base, motion-base, or head-mounted simulator. The choice is an extremely difficult one when it comes to evaluating which simulator will significantly reduce sickness. We fully realize that this is not the only issue when deciding among simulators or even the primary issue; but it is the only one which we will discuss here. Ideally, there would be a common set of scenarios and one could simply compare the sickness rates for the simulators of interest. But, such a database does not exist.

If simulator sickness is likely to be of real concern to a researcher, either because of the participants being selected (e.g., older drivers) or the scenarios being used, then one may need to exercise special care when adding motion or using a head-mounted display. As a general rule, motion cues appear to decrease simulator sickness or leave it unchanged. Various studies on the effectiveness of motion cuing are discussed in the section on motion cueing. As for head-mounted displays, typically they are fully immersive, making it difficult for participants to maintain the correct rest-frame. Moreover, additional demands are placed on the hardware because head movements now need to be tracked precisely. These characteristics make simulator sickness more likely with head-mounted displays. The issues for head-mounted displays are different than those for fixed- or motion-based displays and are discussed below in their own section.

14.6.1.2 Field of View

As noted above, field of view has long been implicated as a contributing factor to simulator sickness (Kennedy, Lilienthal, Berbaum, Baltzley, & McCauley, 1989; Casali, 1986; Kolasinski, 1995; Pausch et al., 1992). While the effects of vection and resulting simulator sickness have been reported in fields of view as narrow as 15 degrees (Andersen & Braunstein, 1985), a greater field of view tends to be an elevating factor (Ijsselsteijn, Ridder, Freeman, Avons, & Bouwhuis, 2001). This is because wide fields of view have the potential to stimulate more of the peripheral visual system, which in turn results in greater optic flow and vection (Kennedy et al., 1988; for a review, see Andersen, 1986). However, there is no study of which we are aware that specifically quantifies the relationship between increases in the field of view and increases in sickness. There is one interesting finding discussed below which may deserve more investigation. In particular, at least in some circumstances, it would appear that providing special glasses which restrict the field of view in a wide field of view simulator leaves performance unchanged (Van Erp & Kappé, 1977; Pepper, 1986; Spain, 1988). If this is the case, then one can reduce optic flow and potentially the associated simulator sickness without affecting performance by simply designing a simulator with a relatively narrow field of view.

The simulation designer is faced with a trade-off where the visual system should have just enough field of view to support the requirements of the task being performed but not so much that optic flow becomes a problem (Stanney, Mourant, & Kennedy, 1998). The field of view required for driving ground vehicles varies depending on the experimental tasks being performed. In normal highway driving, the driver needs to be able to scan the environment ahead to determine the physical shape and orientation of the roadway in addition to acquiring self-motion information from the optic flow. At intersections, the driver needs less information about self-motion but has an additional requirement to scan left and right looking for potential hazards and checking for traffic. In this case, a 180-degree forward field of view would be ideal to safety negotiate an intersection. The requirements of off-road driving are also likely to include an ability to scan a wide field of view as the driver searches for hazards and looks into and around tight, winding roads.

14.6.1.3 Calibration of Eye Height: Simulator Design Eye

Care should be taken to position the viewer in the appropriate location such that the image presented from the eye point in the simulator (the simulator design eye) matches the eye point of the actual operator. Typically the height of drivers will not have a significant affect on where the displays need to be placed; however, a slight change in the driver location in the vehicle can have a significant effect on the optic flow and visual information. The slight change can come from something as simple as a head movement, a real problem in flight simulators (Kennedy et al., 1987). This is not as much of a problem for drivers in a ground vehicle simulator. However, the passenger seated in the simulator will not receive the same cues as the driver given the position in the vehicle (the simulator design eye and the passenger's point of view are different in this case) and will be much more susceptible to simulator sickness (Riccio & Stoffregen, 1991).

14.6.1.4 Display Alignment

Many simulators use multiple screens to project a virtual world that surrounds the driver. If misaligned, the misalignment can cause simulator sickness (see Hettinger et al., 1987; and Kennedy et al., 1987, for a more detailed discussion). Briefly, there are three reasons that simulator sickness could increase. First, unless viewed from the geometric center of projection, displays of the 3D world introduce distortions (Rosinski, 1982). Second, if the displays are not aligned, then the participant would experience the same scene but as if from different viewpoints (see also Andersen, this book, chap. 8). This would lead to intrasensory cue conflict. Finally, if the scenes have different virtual distances then they would be at different accommodative focuses. This could result in fatigue and headaches from the constant switching.

14.6.1.5 Scale

Images in the virtual world often appear as scaled (minified or magnified). The geometric field of view is defined as the angle subtended by the near or far plane in the viewing frustum. If the observer were sitting at the computed center of projection and the far plane was displayed on a screen just equal to the vertical and horizontal boundaries of the far plane, the image would be perfectly scaled. However, if the screen is closer it will be magnified; and if it is further it will be minimized. In order to test whether image scale had an affect on simulator sickness, Draper, et al. (2001) asked participants to navigate a virtual world which was minimized (0.5), to scale (1.0), or magnified (2.0). A head-mounted display was used. Thus, the feedback from the vestibulo-ocular reflex in the minification and magnification conditions was in conflict with the change in the visual information in the scene. Participants were asked to complete the SSQ both before and after being exposed to the virtual environment. The absolute values on the pre-test and post-test SSQ were much smaller in the neutral condition. Moreover, both minification and magnification led to larger changes in both the pre-test and post-test scores.

It seems clear that one should do as much as possible to ensure that there is no magnification or minification.

14.6.1.6 Image Resolution

Image resolution can have a marked effect on task performance and may also contribute to simulator sickness. A healthy human eye can perceive an image that subtends an angle of about 1 arc minute (arcmin) onto the foveal part of the retina. One arcmin/pixel resolution roughly equates to about 20/20 vision. Many driving simulators today have effective resolutions of about 3–5 arcmin/pixel (Kemeny, 2000; Jamson, 2001) which equate to 20/60 – 20/100 vision. The Federal Aviation Administration (FAA) requires their aviation training simulators to have effective resolutions of 3 arcmin/pixel or less. A simulator with a 180-degree field of view and a 3 arcmin/pixel geometric resolution would require three projectors that each have a horizontal pixel count of at least 1,200. Geometric and effective resolutions are two different measurements of image resolution. Effective resolution is determined by the geometric resolution along with what is known as a Kell factor. The Kell factor accounts for losses in the projector itself, cabling, lens quality, brightness, contrast ratio, etc. (Robin, 2003). A geometric resolution to reach vision limits (1 arcmin/pixel) would require a minimum of 27 such projectors to display the same visual field.

The resulting effects of limited resolution can include drivers missing key features that they should be able to perceive in the environment and potentially causing some amount of eye strain as the eyes attempt to resolve images that cannot be brought into focus (Govil et al., 2004). Moreover, with poor resolution there are potential trade-offs between required contrast, luminance, and resolution (Pausch et al., 1992), leading to potential complications with flicker fusion. Finally, it is possible that the higher resolution displays actually increase optic flow. Very high resolution displays now exist (e.g., 4096 × 2160, Sony Electronics, 2008) and could be used to evaluate the effect of the greatly improved resolution on the development of simulator sickness. However, direct links of the resolution level to simulator sickness have not been made.

Image resolution would appear to have a more direct impact on task performance than on simulation sickness. However, attempts should be made to increase resolution to a level that is sufficient for reducing eye strain while making it possible to extract task-relevant information from the scene.

14.6.1.7 Graphics Update Rate and Refresh Rate

The graphics update rate is the rate at which the display is updated based on the most recent interpretation of information concerning the vehicle state within the virtual environment (it influences the transport delay, discussed separately below). The graphics update rate is typically a function of the capability of the graphics generation hardware/software and the complexity of the visual scene and moving models. The relationship is one of inverse proportion whereby higher levels of complexity typically result in lower sustainable update rates and dropped frames. Decreased update rates can result in increased lag between a given control input and the presentation of the corresponding update of the state of the simulation system. A system running at 30 Hz without prediction algorithms that interrogates the dynamics and extrapolates the eye point to a future location, will add a minimum of 32 ms to the total lag of the system without even accounting for the time it takes to process the information to provide the viewpoint for the graphics subsystem. Many simulators provide information on graphics refresh rate as a measure of performance. When possible this should be checked to ensure that complex scenes or that addition of many vehicles have not caused the frame rate to drop below 30 Hz. Ideally, the scene should have a graphics refresh rate of 60 Hz.

Frank et al. (1988) found that delays in the update of visual information were more disconcerting to simulator drivers than were delays in the update of the motion system. A graphic update rate of 10 Hz presenting an out-the-window view of a vehicle driving at 55 mph will only be updated every 8 feet. The resulting presentation appears "jerky" and has the potential to be perceived as flicker (Casali, 1986). The update rate would need to be at 30–60 Hz for typical vehicle operating speeds.

Refresh rate is the rate at which the display system re-draws the graphic view generated by the image generation system. Refresh rate is independent of the vehicle simulation and the rate at which it processes. Each refresh of the visual scene will present the current state of the graphical output from the image generator. So if the image generator was running at 30 Hz and the display system was capable of running at 60 Hz, each of the 30 Hz graphics frames would be drawn twice by the display system. Refresh rate has the potential to impact sickness if the rate is not constant or if it is slow enough that flicker can be detected (e.g., Harwood & Foley, 1987; Pausch et al., 1992; Rinalducci & MacArthur, 1990). Today's hardware and software are typically able to maintain consistent refresh rates of 60 Hz mono or 48 Hz stereo. At normal illumination levels, the refresh rate should not have an impact on simulator sickness in a modern driving simulator.

14.6.1.8 Transport Delay and Vehicle Control

Transport delay refers to the amount of time it takes to detect an operator input, process the new state of the simulator based on the input, and return to the operator the resulting changes in the state of the simulation above and beyond the lag in the vehicle being simulated (delays in the graphics update rate are just one example of transport delay). In the world of flight simulation it is given a precise definition (Federal Aviation Administration, 1994): "It is the overall time delay incurred from signal input until output response. It does not include the characteristic delay of the airplane simulated (p. 3)". The effect of transport delays (either in motion or visual information) is believed to cause additional sensory conflict between the visual and vestibular systems that might lead to simulator sickness and performance decrement (Draper, 1996; Frank et al., 1988; Pausch et al. 1992). In addition, in driving simulators, visual delays combined with missing vestibular cues can also cause self-induced steering oscillations which can exacerbate the problem through increases in visual artifacts caused by yaw rotation in the display. When simulators lack haptic cues they eliminate "lead" from the input to the driver, undermining stability. An important consequence of the reduced control is increased steering input and consequently more vection and greater mismatch between visual and vestibular cues as the car swerves back and forth. This instability might be an important cause of simulator sickness and could serve as an early warning of potential simulator sickness.

Cunningham, Chatziastros, von der Heyde and Bultoff (2001) manipulated visual transport delays to steering inputs on a high-fidelity, floor-mounted driving simulator. They evaluated steering performance as a function of these delays as drivers negotiated a curved route at fairly high speeds. Their goal was to determine how drivers adapt to the delays and if the adaptation transfers to other driving conditions. The delay values they used were 130, 230, and 430 ms. In their first experiment, they found that drivers did learn to adapt to the delays, but the longer the delay, the longer the adaptation period. In addition, they found that a subsequent removal of the delay resulted in a renewed decrement in performance. In their second experiment, they determined that the adaptation or learning accomplished in the first experiment generalized to a variety of different road types. So, while subjects can adapt and learn to drive with significant transport delay, their speed of learning and subsequent unlearning will depend on the magnitude of the delay. The longer the delay, the longer the time period required to adapt. A threshold of how small transport delay must be to maintain real-world (non-adapted) driving performance is not yet known. At least one author (Kemeny, 2000, citing Bloche, Kemeny, & Reymond, 1997) indicates that the value must be less than 50 ms.

Frank et al. (1988) performed a driving simulator study to determine the impact of both motion and visual delay and found that visual delay was more disconcerting than motion delay. They concluded that both visual and motion delay should be minimized but it was more important to minimize visual delays if trade-offs needed to be made between the two.

The effect of transport delay on driving simulator drivers is not well understood, or even calculated in most cases (Kemeny, 2001). Yet, it is perhaps the most important measure of simulator performance.

14.6.1.9 Motion Cueing

Motion systems have been added to many modern driving simulators in hopes of increasing realism and the validity of operator responses while also reducing simulator sickness. There are several different types of motion that are used. These types are vibration, small amplitude deceleration cues (1–4 inch movement), large amplitude tilting (hexapod), and large amplitude track. It is difficult to determine what type of motion is the best in terms of reducing simulator sickness because so few simulators are equipped to produce the requisite experimental conditions.

Even with the most capable motion-base available, it is impossible to duplicate the large accelerations felt in an aircraft or in ground vehicles. Other strategies must be used, such as scaled cueing and washout algorithms. Scaled cueing is a technique where a scaling value is applied to the forces being applied to the driver in the simulator. At a scaling factor of 0.25 and a real-world deceleration of 0.4 g, the driver of the simulator would experience a 0.1 g deceleration. Scaling allows for proportional acceleration inputs without extending the simulator beyond the limits of the motion hardware.

When motion is used in driving simulation, the impact on performance depends somewhat on the maneuvers being performed. Advani and Hosman (2001) state that driving skill-based behaviors are affected much more by motion cues than knowledge-based behaviors. Therefore, motion cues will have greater impact on vehicle disturbance and recovery maneuvers than on lane tracking tasks. The driver relies on the quality of the motion cues and close-coordination of corroborating visual information to make appropriate responses.

There are a number of studies where positive results on simulator sickness have been found from adding motion cueing (Casali, 1986; Curry, Artz, Cathey, Grant, & Greenburg, 2002). For example, Curry et al. conducted a study to compare their fixed-based simulator to their 6 DOF motion-base simulation. Their fixed-base simulator has a 140-degree horizontal field of view system and the motion-base system has a 180-degree horizontal front field of view plus 125 degrees to the rear dome on a 6 DOF motion-base. After conducting similar driving tasks for an equal amount of time, they reported lower simulator sickness questionnaire (SSQ) scores for those subjects that drove the 6 DOF motion-base simulator. Several authors (Sharkey & McCauley, 1992; Barrett & Thornton 1968) indicate that perhaps less expensive, higher frequency vibration transducers mounted on the occupant seat might help mask some of the proprioceptive and vestibular cues that might conflict with visually implied motion. In addition, real-world driving applications typically include some amount of higher frequency vibration, which may be an important cue to the perception of vehicle velocity. The mismatch between the true motion of the vehicle and the motion produced by the simulator actuators can induce simulator sickness, with a mismatch in the frequency range of 0.06 to 0.07 Hz being most critical.

However, it is important to understand that motion cues may lead to no discernable differences in simulator sickness (Sharkey & McCauley, 1992; Barnes, 1987; Hettinger, Berbaum, Kennedy, & Dunlap, 1990; Kennedy et al., 1993), or may actually make things worse. The exact factors that contribute to the success or failure of using physical motion cues to reduce cue conflict do not appear to have been determined, and there are few motion systems able to produce non-scaled cues.

14.6.1.10 Head-Mounted Displays

Head-mounted displays (HMD) offer a number of potential advantages to driving simulation applications. First, there is a freedom from visual field of view restrictions experienced when implementing traditional fixed-display technologies. Wider fields of regard are required to perform appropriate visual search and monitoring tasks while driving. With appropriate head tracking technologies, the effective field of regard could be as much as 360 degrees. Second, there is much less infrastructure required to support HMD-based systems due to the elimination of the physical display medium. In addition, the reduced overall footprint of HMD-based simulation systems make them more portable, increasing their applicability to a wide variety of driving applications. Lastly, the cost and complexity of HMD-based systems might also be lower due to elimination of physical display infrastructure and also a reduction in the required graphics generation requirements. Where in some traditional simulator implementations several graphics generators or channels are required to create a wide field of view visual scene, the HMD-based system would only require a single graphics generator. Even though there are a number of compelling potential benefits to applying HMD technologies in driving simulation, there are also some potential drawbacks.

While current HMD technologies provide unlimited field of regard, there are serious restrictions on instantaneous field of view (the field of view visible when the head is still). Most systems offer fields of view that are 50 to 25 degrees horizontally, a width which can be expanded by modifying the amount of ocular overlap. (For a more complete review of HMDs, see a recent article by Patterson, Winterbottom, & Pierce, 2006). Human eyes have an approximate 120-degree horizontal overlap between their fields of view. An ideal head-mounted display system will allow both eyes to clearly see what the other can see within this overlapping region. Most HMDs have two independent channels, one for each eye, and some designs do not fully support this overlapping region in a way that makes sense to the brain. Therefore, it is important to understand the viewing requirements of the simulation and the locations of objects that will need to be observed. Without 100% overlap, objects close to the viewer may cause disorientation as the eyes cannot see the images as the brain expects them to be seen. For instance, partial overlap can lead to visual illusions such as the appearance of a curved moon at the monocular border where binocular rivalry is greatest. The most appropriate modification of ocular overlap for a general driving simulation application has yet to be determined, but will likely be something less than 100%. Regardless, the failure of ocular overlap could lead to symptoms of simulator sickness.

To understand the impacts of reducing the field of view from our unmodified capability on performance and simulator sickness, we must refer back to the basic functions of the anatomy of the eye. Recall from the earlier section on central versus peripheral vision that central vision is good for static viewing and identifying what something is; peripheral vision is good for motion sensation, spatial orientation, and supporting gaze stability (Leibowitz, 1986). With respect to driving, Leibowitz notes that experienced drivers tend to use peripheral vision for steering the vehicle while using central vision for identifying potential hazards in the world. If instantaneous field of view is limited with the HMD, there may be an effect on the driver's ability to effectively steer the vehicle. For instance, Wood and Troutbeck (1994) found that with narrow fields of view it is more difficult to drive a vehicle in a straight line down a straight road. This can easily contribute to simulator sickness since there are no corresponding vestibular cues.

In an evaluation of several display types with pilots performing a flying task, de Vries and Padmos (1998) found that operator performance was worse with the HMD than with head-slaved or full screen displays. However, they attributed the performance reduction to the considerable image delay (190 ms) and heavy weight of their system as opposed to field of view reduction. They came to this conclusion because a limited field of view head-slaved option did not result in a corresponding reduction in performance. They go on to recommend adding vehicle references when using HMDs to help provide a stable reference from which adjustments of orientation can be made. This could also potentially reduce symptoms of simulator sickness if the rest-frame theory of simulator sickness explains why drivers develop such symptoms (Prothero, 1998). Kappe and Padmos (2001) performed a study similar to the one above in order to evaluate the effects of HMD, widescreen, and head-slaved displays on ground vehicle driving performance. They found similar results where the HMD resulted in a negative effect on driving performance.

In an assessment of a fixed-base driving simulator that makes use of an HMD, Mourant and Thattacherry (2000) found that subjects reported more oculomotor discomfort symptoms on an SSQ than what has typically been found in driving simulation studies using the SSQ. They attribute the shift from more nauseogenic symptoms to oculomotor symptoms to advances in virtual environment technology.

Burns and Saluaar (1999) conducted an evaluation of driver behavior using an HMD in a driving simulator as they negotiated their way through intersections and ensuing turns. They found that drivers with the HMD made longer glances but also made the same number of glances as did drivers in a real vehicle. They also found differences in driver's speed after turns, lane keeping ability, and subjective workload where use of the HMD decreased performance and increased workload. In a more theoretical study evaluating perception of self-rotation with an HMD, a widescreen, and a widescreen with field of view limiting blinders, Schulte-Pelkum, Riecke, and von der Heyde (2003) found that, in general, subjects tended to underestimate the amount of rotation they had experienced, but underestimated to a greater extent with the head-mounted display. They concluded that the effect had to do with something other than field of view given the significant difference between the performances in the HMD versus the widescreen with limited field of view blinders. In a second study, Schulte-Pelkum, Riecke, von der Heyde and Bülthoff (in press) evaluated the effects of curved versus flat screens in perception of eco-rotation through visual stimuli. They found that subjects underestimated rotation with curved screens but overestimated rotation with flat screens presenting the same field of view. They attribute the differences to subjects perceiving rotation as translational movement with the flat screen displays. It is not clear how these differences affect simulator sickness, if at all. The cue conflict associated with expected and actual rotation may contribute to simulator sickness, particularly if it also contributes to steering over corrections and high levels of vection.

Ruspa, Scheuchenpflug and Quattrocolo (2002) evaluated two simulator designs that were to be used for ergonomic vehicle evaluation. The first configuration was a 100-degree horizontal field of view fixed display system and the second used an HMD with 40-degree horizontal field of view. Data collected with these systems was compared with some data collected in actual vehicles. The key finding was that the subjects did not necessarily make use of the additional field of regard that was afforded by the HMD. In a backing task in the real vehicle, 28 of 36 subjects turned around to look while backing. In the HMD condition, only 1 of the 36 subjects turned around to look while backing. Others have reported a reduction in head movements while using HMDs (de Vries & Padmos, 1998; Burns & Saluaar, 1999). Wells and Venturino (1990) conducted a study of subject's performance on a target detection task with wide and narrow field of view HMDs. With the wider field of view, subjects moved their heads less but at faster rates when they did. The reduction in normal head movement might be caused by several factors. The weight and inertia of the hardware itself might be enough to cause some not to move their heads often. If display lags or tracking errors exist, some may not move their heads to avoid the "penalty" of experiencing the feelings of discomfort that these effects can bring. If HMDs do result in a reduction in voluntary head movement, it would likely result in reduced performance on driving tasks, especially in environments where a lot of lateral scanning is required. Note that while such a reduction affects the generalizability of the results obtained on an HMD, it would actually act to reduce simulator sickness since there are fewer chances for conflicts cues produced by the vestibulo-ocular reflex and the visual display.

There appears to be a trend in the literature to date that would indicate that driving performance will be worse with HMDs. Several studies have evaluated theoretical HMDs where a widescreen simulator system is used but a field of view restriction is placed on the driver through special glasses or masks (Van Erp & Kappé, 1977; Pepper, 1986; Spain, 1988). These represent "perfect" HMDs in that there is no latency or head tracking error and the weight of the head-mounted hardware is minimal. These studies have failed to find any differences between their "perfect" HMDs and widescreen simulation display. Therefore, this has caused some to hypothesize that it is not the field of view restriction that negatively impacts performance but rather it is the visuomotor interference which is caused by tracking latency and error that is the culprit. The real question is whether technical advances such as faster processors, more accurate tracking, and better prediction algorithms can solve or partially eliminate performance disparity. Given the potential benefits of being able to use HMD technologies including reduced overall costs, smaller footprint, etc., the issue certainly deserves more investigation and research. From the standpoint of simulator sickness, this leads to the interesting hypothesis that special glasses could reduce simulator sickness by augmenting floor-mounted wide field of view simulators. However, this needs further research and empirical evidence.

The relationship between HMDs and simulator sickness was referred to at several different points in the discussion. We now want to address this relationship more directly. The total impact of HMDs is as yet unknown. As noted previously, it has been shown that an increase in simulator field of view and the resulting increases in peripheral stimulation cause increases in simulator sickness (Kolasinski, 1995). Therefore, it is possible that the field of view limitations caused by HMDs might actually reduce simulator sickness (Pausch et al., 1992). Of course there are a number of other less optimistic factors that need to be considered as well. Most lighter weight HMDs make use of LCD technologies. Image smear caused by phosphor decay in rapidly moving images from LCD displays has been theorized to be a contributing factor to simulator sickness.

Additionally, HMDs require head tracking in order to present the appropriate orientation of view. Thus the transport delays described above can be severe where there is latency and error in the data being fed to the visual system; and the more severe the delays the more likely is simulator sickness to occur. Specifically, latency affects the visuomotor system in that it triggers a change in the vestibular ocular reflex response in order to accurately stabilize the image on the retina. The adaptation does occur naturally but will take some period of time to accomplish—anywhere from five minutes to several hours, depending on how much adaptation is required and how consistent the change. Variance and error in latency response can cause a prolonged adaptation period (Draper, 1996). This finding indicates that if you are going to be "off" with the tracking values, it is better to be consistently off so the visuomotor system can adapt to the error. The longer the subject experiences the sensory stimulus without adaptation, the greater the potential for sickness. To forgo the adaptation process, it would be necessary to reduce latencies in the head tracking processes down to around 50 ms (Kemeny, 2000).

Several HMD hardware design factors can have an impact on potential simulator sickness. The weight and inertia of HMDs has also been implicated as a potential cause of simulator sickness. HMD weight can affect the body's interpretation of the mass of the head and subsequent movements will distort the signaling produced by the otoliths responsible for perceiving tilt (DiZio & Lackner, 1992). This will in turn create a conflict between the proprioceptive and vestibular systems. Controlling for all other factors, Dizio and Lackner (1992) found that the weight of the head-mounted gear alone is enough to trigger sickness symptoms without consideration of any visual stimuli. HMDs with a weight as light as 600 g have been shown to cause sickness.

Inter-pupillary distance (IPD) is a design parameter or an adjustment setting associated with HMDs. The idea is that you adjust the width of the lensing or displays in the HMD to more closely match the individual's natural IPD. With respect to the effects of IPD supported by the HMD, Kolasinski (1995) summarized a study by Regan and Price. They hypothesized that individuals with departures from the design IPD would suffer eye strain, headaches, and visual system problems. They found instead that only those with IPDs greater than the design IPD suffered ocular problems. The majority of persons in their study had IPDs smaller than the design IPD. In those cases, it appears that the eyes are able to converge using normal binocular visual response without discomfort. However, those required to diverge their eyes would experience greater discomfort because this is not typically the way eyes move to resolve an image. Therefore, on systems where the IPD is not adjustable to the individual, it is necessary to make sure the design IPD is greater than the subject population's IPDs. The best approach might be to adjust for each individual and slightly bias towards setting it too narrow.

HMDs offer exciting advantages as display solutions for driving simulators. However, as shown in the discussion above, there are a number of areas where they appear to exacerbate simulator sickness and these areas need further research before the full potential of HMDs can be exploited.

14.6.2 Scene and Scenario Design Factors

Scene and scenario design may offer researchers who have already purchased a driving simulator the largest area for improvement. There are a number of things one can do and these are discussed below.

14.6.2.1 Scene Design

The basic rule of thumb when designing a scene is to reduce the cues in the scene that enhance the perception of optic flow (Figure 14.1) and vection. Scene enhancements such as the use of trees, buildings, or other static objects help give cues of motion to the driver and thus are part of the necessary furniture within the environment. However, the addition that they provide in realism needs to be counterbalanced by the knowledge that these cues are the very ones that create cue conflict for the driver. Researchers who can populate the environment with objects that they can position and then texture have the advantage of being able to adjust the optic flow. So, for example, the trees along the side of road could be placed further back from the road and made sparser. Or, the buildings on an urban street could be covered with as much unbroken wall surface as possible instead of covered with windows that themselves had mullions and other textured elements. The bottom line is that a totally featureless environment has no optic flow and therefore will not produce simulator sickness. But such an environment gives drivers no cues as to location, roadway and speed and therefore is not useful. To our knowledge, no one has explored just how featureless an environment could be and still provide the necessary visual cues to make it possible to generalize the results of the experiment from the laboratory to the real world. One reason for this is that the need for scene complexity depends on the specific driving tasks and research questions: Studies of speed perception will require more sickness-inducing detail than studies of driver distraction.

14.6.2.2 Scenario Design

Movement within the scene is another factor to consider when designing a scenario. In general it is recommended that one should minimize the rapid changes in direction and the number of sharp decelerations. Consistent with this, curves with larger radii and fewer roadside objects produce less simulator sickness than do tighter curves with densely packed objects (Chrysler & William, 2005). In a similar vein, 90-degree left and right turns are definitely known to increase the likelihood that the driver experiences simulator sickness (Edwards, Creaser, Caird, Lamsdale, & Chisholm, 2003; Mourant, Prasanna, Cox, Lin, & Jaeger, 2007; Park, Allen, & Fiorentino, 2006; Watson, 1995; Watson, 1998). Arguably, one can reduce the nausea produced at right angle turns by making such turns into Y intersections as the turn is less sharp. And for most simulators this has the added advantage of making it possible to see traffic approaching from the left or the right.

Interestingly, we also know anecdotally that simulator sickness can be reduced in an HMD by up to 30% if a vehicle does not pitch down as a driver brakes.* Note that such a downward movement of the front end of the vehicle does noticeably occur in the real world, but in the simulated world it does not need to occur. If it does not occur, then the horizon stays fixed as the driver is braking and so the cue conflict is reduced. However, in a fixed or motion-based simulator the opposite has been found.† When the amount of a vehicle pitch corresponds to the appropriate decelerations simulator sickness has been shown to be reduced.

14.6.2.3 Independent Visual Background

The role of an independent visual background was discussed above. Several ways of introducing such a background were mentioned: making the room behind the display visible through the display (Prothero et al., 1999); placing a fixed grid over the display (Duh et al., 2001); or adding an earth-fixed avatar to the display (Lin et al., 2002), one which indicated directions as well as the true rest-frame. Only the latter manipulation was run on a driving simulator. It seems impractical in most studies because the avatar was a plane that was in the upper part of the display, thereby necessarily creating a distraction. However, there seem to be many other possibilities that still need to be explored. For example, would an earth-fixed cloudy sky not only reduce the visual flow, but also help the driver keep in the forefront the correct rest-frame? Would a narrowed field of view in the vertical axis allow for the placement of a grid-like border around the virtual world which kept the driver from being seduced into the rest-frame implied by the cues in the virtual world? Even designing the virtual world so that much of the horizon is visible much of the time might be effective. It seems that there are many possibilities, none of which would be a cure-all, but each may be beneficial.

14.6.3 Environmental Conditions

Temperature has long been thought to contribute to simulator sickness and it is recommended to keep the cab temperature cool

* Personal communication with Konstantin Sizov, President and CEO of DriveSquare.

† Personal communication with James W. Stoner, Professor, University of Iowa.

(e.g., Kennedy et al., 1987). Several physiological changes occur as a result of simulator sickness. Heart rate, blood pressure, respirations, and skin temperature all increase as a result of experiencing a virtual environment (Jang et al., 2002). The relationship that ambient room temperature has with these physiological changes is not yet known but is thought to elevate the magnitude and rate of awareness of simulator sickness symptoms. As a precaution, it is recommended that adequate ventilation and temperature control be built into any virtual environment laboratory (e.g., preferred operating range being less than 70 degrees Fahrenheit). The ventilation and temperature control should take into account the heat produced by the hardware (computers, projectors, etc.) and the number of people generally in the room at the time of operation.

14.6.4 Screening

There are a number of questions one might use to identify participants who are at a greatly increased risk of developing simulator sickness. (Below, in a separate section, we discuss the broader range of individual differences and their often somewhat weaker relationship to simulator sickness.) In general, individuals who have fatigue or sleep loss, a hangover, an upset stomach, head colds, ear infections, ear blockages, pregnancy, or an upper respiratory illness, or who have recently taken medications or alcohol should postpone a session on the simulator (Johnson, 1995; Kennedy et al., 1987). Similarly, individuals who have been sick recently and are not fully recovered should be screened from participating in simulator studies or training.

Individuals should consider not participating if they have ever experienced motion sickness. Such individuals are more likely to experience simulator sickness as well (Allen & Reimer, 2006; Reason & Graybiel, 1972). For example, in one study, 25 healthy participants (21–59 years old, 41.36 years old on average) drove a fixed-based driving simulator (Fagbemi & Peffer, 2006). Nine participants experienced severe symptoms of simulator sickness, 16 did not. Six of these 9 (67%) had reported prior motion sickness whereas only 2 of the 16 (12.5%) in the well group reported previous signs of motion sickness. Exposure is most frequently measured by the Motion Sickness Questionnaire (Kellogg, Kennedy, & Graybiel, 1965).

Finally, as noted above one might want to measure postural stability. Specifically, it will be recalled that Stoffregen et al., (2000) found that prior to the testing, there were a number of differences in postural motion in the sick and well groups. However, these differences did not explain as much variance as do the differences in prior motion sickness, so one would want to use them with some caution.

14.6.5 Online Monitoring

Ideally, screening would be supplemented with online monitoring of an individual to determine whether simulator sickness was developing in those individuals who had passed the screening criterion. Given that no screening criterion is perfect, it makes sense to employ online monitoring as well as screening where possible.

14.6.5.1 Physiological Monitoring

In the study described above by Bertin et al. the continuous monitoring of symptoms of simulator sickness allowed the investigators to determine whether the changes in the physiological variables reliably preceded changes in the level of simulator sickness. Analysis of the results indicated that there were reliable decreases in skin temperature and skin resistance before the quick rise in self-reported simulator sickness. If one is going to use such information in an ongoing research project, one would normally need more information than has been provided to date in the extant studies. At the very least one would need to know something about the number of misses (e.g., individuals with decreasing skin temperature who did not get sick) and false alarms (e.g., individuals with constant or increasing skin temperature who did get sick) in order to identify the exact level of a physiological variable which maximizes the expected gain, however defined. Such studies have not been performed to date but clearly are of merit. Even if physiological instrumentation is not available, some physiological responses are visible to the experimenter, such as pallor, sighs and pronounced swallowing. These cues can be a useful indicator of discomfort and can be used to query the participant about feelings of discomfort.

14.6.5.2 Postural Stability

Postural stability, if monitored intermittently, can also help an investigator predict who is and who is not likely to develop symptoms of simulator sickness. Smart, Stoffregen and Bardy (2002) show that there is a strong correlation between changes in various indices of postural stability early in a simulator experiment and later sickness. Specifically, standing participants were exposed to an optical simulation of body sway. The symptoms of motion sickness were explained to participants prior to the experiment and they were told to end their participation as soon as any of these symptoms appeared. Postural stability was measured throughout. Changes were noted in measures of the variability, range and velocity of postural motion that preceded changes in the simulate sickness scores. The particular subset varies from one experiment to another (Stoffregen & Smart, 1998; Stoffregen, Hettinger, Haas, Roe, & Smart, 2000; Smart et al., 2002), but this is to be expected.

14.6.6 Breaks and Task Time

One general rule to follow is that the total simulation exposure should not last more than two hours (Johnson, 2005). The longer the period of performance in the simulator the more likely the discomfort level experienced will increase. Frequent breaks between drives are also recommended with a single drive lasting no more than an hour. Also, the more aggressive the scene and scenario is the shorter should be the duration of the driving session. Typically researchers use the guidelines where drives should last between 5 and 25 minutes with 10 minute breaks. To our knowledge there is no set rule or study that quantifies these exposures, but it is the general practice in the industry.

14.6.7 Simulator Practice and Adaptation

The human nervous system is a very complex set of mechanisms and processes but is also highly adaptable. This is evident from examples of micro processes discussed earlier, such as the adaptation of the vestibulo-ocular reflex and optokinetic responses with variations of input stimuli. At the same time, it is also generally accepted (Kennedy, Stanney, & Dunlap, 2000) that simulator sickness increases with time within a session and decreases over successive sessions. These effects have been confirmed and may vary as a function of scenario intensity as measured by scene complexity and number of moving models, and consistency of the cue presentation factors (Watson, 1997; Watson, 1995).

In a study to quantify adaptation as a function of scenario intensity and motion cueing, Watson found that SSQ total sickness, disorientation and ocular discomfort scores dropped by as much as 2/3 from the first to the third exposure. However, nausea subscale scores only showed a decline after the sixth exposure resulting in a recommendation of five or more sessions to allow subjects to become adapted. Watson also recommends limiting scenario intensity during the first few exposures to help facilitate adaptation (see also Kennedy et al., 1987). McCauley and Sharkey (1992) make similar recommendations including keeping exposure durations short and limiting aggressive maneuvers.

The issue of adaptation raises some interesting questions with regards to exposure and validity of application results. Applications of driving simulation such as research, training, design validation, etc., are typically challenged when it comes to available simulation resources. Cost and logistical constraints often result in users trying to get the most from the simulation in the shortest period of time. This conflicts to some degree with the recommended practices of allowing simulator drivers multiple (relatively benign) sessions to adapt before getting to the experimental phase of the simulation application. Without understanding the effects of simulation exposure on driver performance and motivation, it is difficult to generalize research results in the simulator to real driving. Early driver training scenarios have the potential to result in less transfer of training simply because drivers are learning to drive the simulator as opposed to focusing on the lessons that the scenarios hold. Regardless of the application, the users of simulation should strive to understand the effects of exposure and adaptation on their expected results.

14.6.8 Individual Differences

A number of individual differences are known to influence simulator sickness. These include susceptibility to motion sickness, current health status, age, concentration level, ethnicity, experience with the real-world task, experience with a simulator (adaptation), flicker fusion frequency threshold, gender, illness, personal characteristics, mental rotation ability, perceptual style, and postural stability. A review of the relationship of each of these individual differences to simulator sickness can be found in Goldberg and Hiller (1995). We focused above on the individual differences which serve as the standard screening questions one would use to identify those with a greatly increased risk of developing simulator sickness. Here we want to focus on one additional individual difference, age, because of the critical importance of understanding the behavior of older drivers in a society with that has an increasing amount of older drivers, many with a greater risk of crashing.

Although age is perhaps the largest individual difference of relevance, there does not appear to be a recent, comprehensive review of how the sickness rates vary with age (Johnson, 2005). Perhaps the largest database that was reviewed was back in the early 1990s. Hein (1993) analyzed the results from 22 separate studies, all undertaken on the fixed-base driving simulator owned by the Hughes Aircraft Company. A total of 469 participants were involved in the studies, the age range varied considerably. Hein reports that "older drivers ... are severely susceptible to simulator sickness (p. 611)". Having said that, the sickness rates across studies vary widely even when controlling as much as possible for field of view, stops and starts, and frequency of turns.

For example, in one recent study, 57 men and 127 women between the ages of 60 and 99 (average of 77) were enrolled (Freund & Green, 2006). Participants in this study sat in an adjustable car seat, used standard accelerator and brake pedals, and had a standard size steering wheel mounted on a dash. The virtual world was projected on three 4 by 3 foot screens in front of the cab subtending 130 degrees of visual angle side to side. The participants had to drive for 30 minutes through urban scenarios which required left and right turns at four way intersections and changes in speed, including coming to a complete stop. In short, the scenes and scenarios were ones which should lead to a relatively high rate of simulator sickness; yet, only 10.6% of the participants became sick, as indicated by reports of lightheadedness, dizziness, nausea or vomiting.

Contrast this with a study run by Edwards et al. (2003). Twelve older drivers between the ages of 65 and 83 (average of 71.4) and twelve younger drivers between the ages of 19 and 25 (average of 20.7) were enrolled. The simulator here was similar to the one in the study above, except that participants now sat in an actual vehicle. The screens were slightly larger, subtending 150 degrees of visual angle side to side. However, the drives (as best we could tell) were almost identical and included intersections, signals, pedestrians and traffic. Yet, even with such similar scenarios and simulator design, fully 40% of the older adults became sick as opposed to only 10% in the above study. It is not clear what differences between these two studies explain the dramatic difference in simulator sickness rates.

As predicted by the evidence provided above, one would expect to find—and one does find—that decreases in the number of turns decreases the level of sickness. So, for example, in a study involving older adults on straight roads only 12.5%

became sick (Edwards et al., 2003). This suggests that one can obtain acceptable sickness rates with older adults, but with some real constraints on the types of scenarios one can use to evaluate driver performance.

14.7 Conclusions

Simulator sickness has been an important concern from the first application of simulators over 50 years ago. Although many strategies can help reduce simulator sickness, even the most carefully tuned simulator can make participants feel ill. The motion sickness that some people feel on some types of roads demonstrates this challenge. Four theories reflect the most common explanations of simulator sickness: sensory cue conflicts, the body's response to position, postural instabilities, and rest-frame inconsistencies. These theories offer suggestions for minimizing simulator sickness which include tuning the simulator design, adjusting the scenarios and protocol, and monitoring and screening participants:

- Operate with a narrow field of view if possible; the wider field of view, motion-base, and higher resolution screens of higher fidelity simulators have the potential to increase simulator sickness if visual and vestibular cue conflicts are not resolved and vection and optic flow are not managed.
- Calibrate the eye height, align screens, maintain an adequate frame rate (>30 Hz) and ensure minimal transport delay (<50 ms).
- Pay special attention to head-mounted displays because of the potential lags in head tracking, the absence of any obvious earth centered rest-frame, and the special tuning they require.
- Design scenarios that minimize 90-degree turns, tight curves, abrupt braking, and unnecessary optic flow (e.g., picket fences and many roadside objects).
- Keep the simulator cab cool and well-ventilated.
- Use short drives and allow people to adapt to the simulator with an uneventful drive in which they follow a lead vehicle for several minutes.
- Acclimatize people over as many as six sessions to help minimize simulator sickness.
- Monitor simulator sickness during an experiment if at all possible by observing the participants carefully as they drive, and after the experiment using the SSQ.
- Screen participants to avoid those who are particularly susceptible to simulator sickness, such as those with the following conditions: fatigue or sleep loss, a hangover, an upset stomach, head colds, ear infections, ear blockages, pregnancy, an upper respiratory illness, or those or who have recently taken medications or alcohol.

Key Points

- There is a difference between motion sickness and simulator sickness. While the symptoms of motion and simulator sickness overlap, there are clear differences in the causes of these two different types of sickness.
- There are several different theories of simulator sickness. These include theories that refer to inter- and intramodal sensory cue conflicts, the body's response to position, postural instabilities, and rest-frame inconsistencies. No theory has yet explained or predicted simulator sickness completely.
- Arguably, conflicting cues from the vestibular and visual systems influence simulator sickness the most. The features of each system that are most often in conflict in a simulator are discussed.
- There are several well-validated measures of simulator sickness that could be used in almost any study where simulator sickness is expected as a problem. Because simulator sickness can affect all aspects of driving, without such measures one cannot safely generalize results from a simulator to real driving.
- There are various preventive measures for simulator sickness. These methods such as screening participants, controlling environmental conditions, and scene and scenario design should be used when possible to help reduce sickness.

Keywords: Simulator Sickness, Vestibular System, Vection, Visual System

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