Technical Report 1027

Simulator Sickness in Virtual Environments

Eugenia M. Kolasinski
U.S. Army Research Institute

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13. ABSTRACT *(Maximum 200 words)*

Virtual Reality (also known as Virtual Environment or VE) technology shows many promising applications in areas of training, medicine, architecture, astronomy, data handling, teleoperation, and entertainment. A potential threat to using this technology is the mild to severe discomfort that some users experience during or after a VE session. Similar effects have been observed with flight and driving simulators. The simulator sickness literature forms a solid background for the study of sickness in virtual environments and many of the findings may be directly applicable. This report reviews literature concerning simulator sickness, motion sickness, and virtual environments. Forty factors that may be associated with simulator sickness in virtual environments are identified. These factors form three global categories: subject, simulator, and task. The known and predicted effects of these factors on sickness in VEs are discussed. A table summarizes the information presented in this report. The information can be used as a guide for future research concerning simulator sickness in virtual environments.

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Technical Report 1027

Simulator Sickness in Virtual Environments

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FOREWORD

The Army has made a substantial commitment to Distributed Interactive Simulation (DIS) and the electronic battlefield for training, concept development, and test and evaluation. The current DIS training System—Simulation Networking (SIMNET)—and the next generation system—the Close Combat Tactical Trainer (CCTT)—provide effective forms of training for soldiers fighting from vehicles, but these systems are unable to do the same for individual dismounted soldiers. Virtual Environment (VE) technology has the potential to provide Individual Combat Simulations (ICS) for the electronic battlefield. However, our initial research in the use of VE technology indicated that some participants experienced simulator sickness—a pattern of symptoms including nausea, headaches, and disorientation. This has implications for both training effectiveness and safety. As the first step in identifying ways to reduce the severity of these symptoms, we reviewed the research literature on the factors involved in simulator sickness.

This report describes the result of that literature review. In addition to influencing future research plans, the research has directly influenced the approach being used in technical advisory service provided to Headquarters, U.S. Army Training and Doctrine Command, on simulator sickness in combat vehicle trainers.

The U.S. Army Research Institute for the Behavioral and Social Sciences (ARI) conducts research to improve the effectiveness of training simulators and simulations. The work described is a part of ARI research task entitled VIRTUE—Virtual Environments for Combat Training and Mission Rehearsal.

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SIMULATOR SICKNESS IN VIRTUAL ENVIRONMENTS

EXECUTIVE SUMMARY

Requirement:

The Army has made a substantial commitment to Distributed Interactive Simulation (DIS) and the electronic battlefield for training, concept development, and test and evaluation. The current DIS training system—Simulation Networking (SIMNET)—and the next generation system—the Close Combat Tactical Trainer (CCTT)—provide effective training for soldiers fighting from vehicles, but are unable to do the same for individual dismounted soldiers. Virtual Environment (VE) technology has the potential to provide Individual Combat Simulations (ICS) for the electronic battlefield. However, initial research in the use of VE technology indicates that some participants experience simulator sickness—a pattern of symptoms including nausea, headaches, and disorientation. This has implications for both training effectiveness and safety. This report is the first step in the identification of ways to reduce the occurrence and severity of these symptoms.

Procedure:

Since the research literature of simulator sickness in VEs is very limited, the literature on sickness in other types of simulators and, to a lesser extent, the literature on the related phenomenon of motion sickness, were reviewed. The factors believed to affect the duration and severity of simulator sickness were organized into three groups: simulator factors, task factors, and individual factors.

Findings:

Although there is debate as to the exact cause or causes of simulator sickness, a primary suspected cause is inconsistent information about body orientation and motion received by the different senses, known as the cue conflict theory. For example, the visual system may perceive that the body is moving rapidly, while the vestibular system perceives that the body is stationary. Inconsistent, non-natural information within a single sense has also been prominent among suggested causes.

Although a large contingent of researchers believe the cue conflict theory explains simulator sickness, an alternative

theory was reviewed as well. Forty factors shown or believed to influence the occurrence or severity of simulator sickness were identified. Future research is proposed.

Utilization of Findings:

This literature search provides a framework that can be used to conduct future research to reduce the occurrence of simulator sickness in virtual environments. In addition, it has directly influenced the approach being used in technical advisory service provided to Headquarters, U.S. Army Training and Doctrine Command, to reduce simulator sickness in combat vehicle trainers.

SIMULATOR SICKNESS IN VIRTUAL ENVIRONMENTS

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APPENDIX A. POTENTIAL FACTORS ASSOCIATED WITH SIMULATOR SICKNESS IN VIRTUAL ENVIRONMENTS A-1

SIMULATOR SICKNESS IN VIRTUAL ENVIRONMENTS

Introduction

"Virtual Reality" (VR) is one of the hottest technologies of the '90s. Already popular in arcades for entertainment purposes, VR (also known as Virtual Environment or VE) technology shows many promising applications in areas such as training, medicine, architecture, astronomy, data handling, and teleoperation (i.e., remote control). Work in VE research centers includes a molecular docking system that has been used to create anticancer medicines, VE-based radiology treatment planning, and VE architectural walkthroughs of building interiors (Rheingold, 1991). Additional examples of VE technology include the Virtuality Dactyl Nightmare arcade game. Matsushita's Kitchen World (a simulated kitchen that can be explored via a virtual environment), and the prototype ski training system by the Nippon Electronic Company Corporation of Tokyo (Antonoff, 1993). Both the U.S. Army and Navy are intently interested in the training applications of virtual environments. As part of its commitment to Distributed Interactive Simulation, the U.S. Army Research Institute for the Behavioral and Social Sciences (ARI) is specifically looking at VE technology in training dismounted infantry on the electronic battlefield (Levison & Pew, 1993).

A virtual environment can be defined in many ways. The definition used for this report is a three-dimensional, interactive, realistic, real-time computer-generated simulation providing direct input to the senses via a head-mounted display (HMD), Binocular Omni-Oriented Monitor (BOOM), DataGlove and similar devices. From the standpoint of a user, there are three major components of a VE system. First, the user must have some way of seeing in the virtual environment. This is usually accomplished with an HMD. Second, the user must have some way of moving through the VE. Joysticks, spaceballs, and wired clothing devices are some of the current devices used to control movement in the VE. Finally, there must be some way to identify the user's direction of view in the VE. This is accomplished by means of a tracking device, often attached to the HMD.

In some ways, the above definition of a VE may be more representative of the goal of VE technology rather than its current state. Today's virtual environment is not necessarily fully three-dimensional, fully interactive, completely realistic, nor carried out in exact real time. Future VE systems will be defined by both technology developments and research on necessary characteristics.

Although this new technology is very promising, there exists a potential threat to the ultimate usability of virtual environments: some users experience discomfort during, and sometimes after, a session in a simulated environment. Similar

reactions have been observed in driving simulators and military flight simulators. This phenomenon is called simulator sickness and it is similar to motion sickness. There is a direct link between simulator sickness and sickness in virtual environments: both are forms of visually induced motion sickness. Thus, the abundant simulator sickness literature, as well as the motion sickness literature, forms an excellent background and starting place in the study of sickness in virtual environments. Although most of the simulator sickness research involves military pilots and flight simulators, many of the findings may be directly applicable to VE systems. These findings can help identify potential factors involved in sickness, as well as suggest ways to combat it.

The goal of this report is to identify factors involved in simulator sickness in virtual environments so that such sickness can be avoided or, at least its severity and duration reduced. To accomplish this goal, much simulator sickness, as well as some motion sickness literature, is reviewed. Some literature specifically applicable to virtual environments is also reviewed, but such research is still scarce because of the newness of the field.

The potential factors fall into three major categories: individual factors, simulator factors, and simulated task factors. These factors are summarized in Appendix Table A1, grouped into the three categories. An outline of Table A1 can be found in Table 1 on the following page.

Table 1

Potential Factors Associated With Simulator Sickness in Virtual Environments

Individual	Simulator	Task
age	binocular viewing	altitude above terrain
concentration level	calibration	degree of control
ethnicity	color	duration
experience with real-world task	contrast	global visual flow
experience with simulator (adaptation)	field of view	head movements
flicker fusion frequency threshold	flicker	luminance level
gender	inter-pupillary distance	method of movement
illness and personal characteristics	motion platform	rate of linear or rotational acceleration
mental rotation ability	phosphor lag	self-movement speed
perceptual style	position-tracking error	sitting vs. standing
postural stability	refresh rate	type of application
	resolution	unusual maneuvers
	scene content	vection
	time lag (transport delay)	
	update rate (frame rate)	
	viewing region	

Within each category, factors are presented in alphabetical order. This is done for several reasons. First, there is no obvious order in which they should be presented. It would be difficult to assign a ranking of "importance" - however one should wish to define this - because a factor's effect is often unknown. In addition, the effects of various factors are different and, therefore, difficult to place along some type of continuum. Thus, factors are arranged alphabetically to give them all equal status in importance. Secondly, factors are alphabetized to aid in using this report as a reference. Every entry refers to a subsection in the text and every factor discussed in the text has a corresponding entry. Details are supplied in the text and Table A1 summarizes important points.

Background

Simulator sickness was initially documented by Havron and Butler in 1957 in a helicopter trainer (Casali, 1986). It is similar to motion sickness, but can occur without actual motion of the subject. The most common symptoms resemble those of motion sickness: general discomfort, apathy, drowsiness, headache, disorientation, fatigue, pallor, sweating, salivation, stomach awareness, nausea, and vomiting. Postural instability, flashbacks (a sudden recurrence of symptoms), retching, and vomiting have also been known to occur. Although the potential discomfort to the subject alone makes simulator sickness a problem, additional drawbacks include adverse consequences to training and user acceptance.

Kennedy and Fowlkes (1992) noted that simulator sickness is properly called a syndrome because of the complex signs and symptoms associated with it. They further noted that some people exhibit all the signs and symptoms, others exhibit only a few, and some exhibit no symptoms at all. Additionally, among people who are symptomatic, no single symptom predominates. Because of the variety of symptoms associated with simulator sickness, Kennedy and Fowlkes described it as being polysymptomatic. Although this characteristic makes sickness difficult to measure, the polysymptomatic nature has an advantage in that symptom differences and changes in symptomaticity may be diagnostic (Kennedy & Fowlkes). For example, if more eye strain is suddenly associated with usage of a particular simulator, it might suggest that something is wrong with the visual display.

Kennedy and Fowlkes (1992) also described simulator sickness as being polygenic since no single factor can be identified as *the* cause. Instead, as this report will reveal, many factors are involved.

Consequences of simulator sickness

To emphasize the significance of simulator sickness, Crowley (1987) identified four important aeromedical and operational consequences: decreased simulator use, compromised training, ground safety, and flight safety. Decreased simulator use may result from pilots who have experienced symptoms and are unwilling to repeat the experience. Training may be compromised in one of two ways. First, symptoms in the simulator may distract the pilot during the session, thus interfering with the training process. Second, pilots may adopt behaviors to avoid symptoms in the simulator which, if transferred to the actual aircraft, may be detrimental. Ground safety in terms of exiting the simulator or driving away from the site may be jeopardized by aftereffects from the simulator such as postural disequilibrium (ataxia) and flashbacks. Such aftereffects, along with any adaptive behaviors (which may have negative transfer effects), may also compromise flight safety after simulator exposure.

Simulator sickness compared with motion sickness

Although simulator sickness and motion sickness have similar symptomatology, they are not the same thing. Tyler and Bard (1949) stated that "Motion sickness is a specific disorder which is evoked in susceptible persons and animals when they are subjected to movements which have certain characteristics" (p. 311). Thus, because of the role of the motion itself in motion sickness, any sickness experienced in simulators incorporating motion (i.e., moving-base simulators) may be true motion sickness. However, many simulators (i.e., fixed-base simulators) do not involve operator motion yet still provoke sickness, since visual stimulation alone can also induce sickness. Thus, although the symptoms of motion and simulator sickness may be similar, their causes may be quite different. Whereas vestibular stimulation alone is usually sufficient to cause motion sickness (Money, 1970), there is no one exact cause of simulator sickness. Simulator sickness is more likely a result of the compounding of the visual and motion cuing and not due to merely the motion alone.

Because of its similarity to motion sickness, any review of the simulator sickness literature necessarily includes some references to motion sickness research. Early studies by Wendt and his associates during the 1940s (cited in Kennedy, Allgood, Van Hoy, & Lilienthal, 1987) related Very Low Frequency (VLF) vibration exposure to motion sickness. In a similar vein, Kennedy, Allgood, et al. (1987) related post-simulator motion sickness symptoms to VLF vibration in moving-base flight simulators. Motion sickness symptoms were assessed with a questionnaire. Of the two simulators investigated, one exhibited motion profiles which, based on other research, fell into a nauseogenic category, whereas the other simulator did not. As

was predicted, pilot reports of sickness increased after exposure to the former simulator whereas exposure to the latter simulator had virtually no effect on reports of sickness. One conclusion from this research is that simulator sickness occurring in motion-base simulators may actually be true motion sickness, since VLF vibration may occur in simulators (Kennedy, Fowlkes, Berbaum, & Lilienthal, 1992). Nonetheless, vision plays an important role in both motion and simulator sickness (Kennedy, Hettinger, & Lilienthal, 1988) - especially because of its influence on orientation and perceived self-motion. In fact, Kennedy et al. (1992) maintained that simulator sickness is primarily visually-induced.

Expected incidence and severity of simulator sickness in virtual environments

In an analysis of data from 10 U.S. Navy and Marine Corps flight simulators, Kennedy, Lilienthal, Berbaum, Baltzley, and McCauley (1989) found that approximately 20% to 40% of military pilots indicated at least one symptom following simulator exposure. McCauley and Sharkey (1992) pointed out that pilots tend to be less susceptible to motion sickness than the general population due to a self-selection process based on their resistance to motion sickness. Since VE technologies will be aimed at a more general population, such selection against sickness may not occur. Thus, McCauley and Sharkey suggested that sickness may be more common in virtual environments than in simulators.

McCauley and Sharkey (1992) also noted that commercial users of VE systems may differ from the typical user of a military flight simulator in terms of their physical and psychological state. Some commercial users may be under the influence of medications, drugs, or alcohol. It is possible that such substances may increase susceptibility to sickness.

Regan (1993) documented the frequency of occurrence and severity of sickness in a commercial, off-the-shelf virtual environment. For 20 minutes, civilian (n=80), military personnel (n=20), and firefighters (n=50) were immersed in a VE consisting of different rooms containing various objects. Subjects were allowed to explore the rooms and interact with the objects. In addition to completing pre- and post-immersion questionnaires, subjects also rated themselves at 5 minute intervals on a 1-6 malaise scale (1 = no symptoms; 2 = any symptoms, but no nausea; 3 = mild nausea; 4 = moderate nausea; 5 = severe nausea; 6 = being sick). At some stage during the 20 minute period, 61% of the 146 subjects reported a highest rating greater than 1. Thus, only 39% of the subjects reported no symptoms. In addition, symptoms were found to be greatest at the 20 minute mark, when 45% of the subjects reported some symptoms. Although she noted that the experimental procedure may have encouraged subjects to

dwell on their physical state, Regan concluded that sickness may be common among users of virtual environments.

Theories of Simulator Sickness

Cue conflict

As Kennedy et al. (1988) pointed out, a comprehensive model of simulator sickness does not currently exist. The primary theory involves discrepancies between the senses concerning information about body orientation and motion. This theory is usually referred to as the cue conflict theory.

Early studies with both fixed-base and moving-base driving simulators implicated cue conflict as the source of the problems (Casali, 1986). To reduce conflicts in fixed-base systems, it seemed logical to add motion to the simulators. Initially, simple random vibration was added, but this alone was not enough to reduce the conflicts. Eventually, advances in simulation made possible the incorporation of acceleration cues which more nearly approximate those actually experienced during driving. Sickness still occurred, perhaps because the visual and motion cues were not in perfect synchrony. Thus, a conflict between the two systems still could have resulted, possibly setting the stage for sickness.

The theory of cue conflict is the most widely accepted theory of simulator sickness. Cue conflict occurs when there is a disparity between senses or within a sense. The two primary conflicts thought to be at the root of simulator sickness occur between the visual and vestibular senses. In a fixed-base simulator, the visual system senses motion while the vestibular system senses no motion. Thus, according to the cue conflict theory, a conflict results. In a moving-base simulator, the visual stimuli experienced may not correspond exactly to the motion which the vestibular system registers. Thus, a conflict can still result.

McCauley and Sharkey (1992) discussed potential sources of cue conflict which could occur in a virtual environment. They pointed out that ambiguities among visual, vestibular, and proprioceptive cues may be created in a VE in the representation of motion because these systems provide visual cues consistent with self-motion, but no corresponding vestibular cues. Such cues are necessary for supporting postural control and locomotion, with vestibular cues and peripheral vision appearing especially important for spatial orientation and self-motion detection. Thus, with ambiguous information, a cue conflict may develop.

Since perceptual and perceptual-motor systems are modifiable, people can learn to function adequately despite

altered conditions such as visual and auditory rearrangements (Welch, 1978). McCauley and Sharkey pointed out that adaptation to a transformed world does not happen immediately. Furthermore, adaptation time depends upon the type of transformation (Welch, 1986). Individuals who adapt quickly may avoid sickness whereas those who adapt slowly may become sick before completely adapting (McCauley & Sharkey, 1992). McCauley and Sharkey offered several potential sources of transformation in a VE including optical distortions, temporal distortions, and the altered correspondence between visual and vestibular information concerning spatial dynamics. They suggested that large transformations and longer exposure times to virtual environments will result in an increased incidence of sickness and will require longer adaptation periods.

The theory of cue conflict provides one explanation for the occurrence of sickness in certain situations, namely, those in which there is a conflict among sensory cues. The theory does not, however, provide any explanation for why sickness occurs from an evolutionary or adaptive point of view. Treisman (1977) proposed just that when he suggested that sickness could be the result of a misapplication of an adaptive mechanism designed to protect an organism. His hypothesis consists of three major arguments. First, the eye-head and head-body systems involved in controlling movement must be highly sensitive in order to carry out their function. Second, neurotoxins in the body can affect movement control. Thus, because of their high sensitivity, the systems which control movement could also function as an early warning system for the detection of toxins in the body. Third, such toxins, if ingested by an organism, usually trigger an emetic response. Putting these three arguments together, Treisman hypothesized that the emetic response associated with motion sickness may be due to a mechanism which responds to ingested toxins but which can also be mistakenly triggered in nauseogenic situations. Furthermore, the nausea and malaise responses may be viewed as an aversive conditioning mechanism which help the organism avoid future ingestion of such toxins. Treisman's hypothesis, which suggests an adaptive benefit for the occurrence of motion sickness, is one of the few explanations for why such effects may occur.

Postural instability

Although cue conflict is the most widely accepted theory associated with simulator sickness, it is not without its critics. One problem several researchers have noted (e.g., Frank & Casali, 1986; Stoffregen & Riccio, 1991) is that it has little predictive power concerning sickness. According to the cue conflict theory, sickness will occur in situations where there is a mismatch between experienced stimuli and expected stimuli. It does not, however, predict which situations will result in a mismatch or how severe it will be. The cue conflict theory only

infers that if sickness occurs then there must have been a conflict. Although this does not necessarily invalidate it, at least one other group of researchers have found enough problems with the cue conflict theory to propose an alternative.

Stoffregen and Riccio (1991) presented a critique of the cue conflict theory from an ecological psychology viewpoint, leading to an ecological theory of motion sickness (Riccio & Stoffregen, 1991). A fundamental aspect of their theory concerns the idea of agreement among or within senses which, according to the cue conflict theory, does not occur in sickness-provoking situations. They referred to this agreement as redundancy and argued that the visual, vestibular, and somatosensory systems might not experience redundant input and such redundancy is not necessarily expected (Stoffregen & Riccio). Input redundancy is a major determinant of sickness according to the cue conflict theory: nonnauseogenic situations are those in which there is redundancy whereas nauseogenic situations are those in which redundancy is lacking. If such redundancy is not a reliable standard for the determination of cue conflict, Stoffregen and Riccio argued that the conflict theory cannot distinguish between nauseogenic and nonnauseogenic situations. In fact, they argued that sensory conflict may not even exist! (Riccio & Stoffregen)

The ecological theory of motion sickness they propose centers on postural stability or lack thereof. (Postural instability, or ataxia, is a possible effect of simulator exposure and is discussed in the next section.) Riccio & Stoffregen (1991) hypothesized that sickness results when the individual lacks or has not yet learned strategies for maintaining postural stability. They argued that postural instability both precedes sickness symptoms and is necessary to produce symptoms. To support their theory, they described how several provocative environments involve postural instability and they also discuss influences on stability. As one piece of experimental support for their theory, Riccio, Martin, and Stoffregen (1992) discussed the results of several experiments in which no motion sickness was reported in what should have been a cue conflict situation. The lack of sickness in these situations, however, is consistent with their theory.

The work of these researchers has been greatly summarized here, but they describe their theory and the theories leading to it in much detail. The interested reader is encouraged to see Stoffregen and Riccio (1988), Stoffregen and Riccio (1991), and Riccio and Stoffregen (1991) for more information.

Although the ecological theory is a competitor to the cue conflict theory, the latter currently remains the most widely accepted theory of simulator sickness, most likely because it has enjoyed wide exposure in the literature and appears to be supported by much of the data. Thus, the rest of this report

will make several references to cue conflict as it relates to sickness. This is not intended to take sides on the cause issue but, rather, is simply due to the fact that the cue conflict theory underlies most of the current research.

Effects of Simulator Exposure

As mentioned in the introduction, the most common effects of simulator exposure resemble the symptoms of motion sickness: general discomfort, drowsiness, pallor, sweating, nausea, and, occasionally, vomiting. These and other typical symptoms are grouped into three major clusters of symptoms - nausea, disorientation, and oculomotor discomfort - by the Simulator Sickness Questionnaire (SSQ) (discussed in the next section).

Along with eye strain, which is identified by the SSQ, and postural disequilibrium, which was discussed earlier as a post-simulator safety concern, two additional effects of simulator exposure - dark focus shifts and changes in performance - have also received attention in the literature. These four effects are discussed in this section.

Ataxia

A major effect of simulator exposure is postural disequilibrium, or ataxia. Thomley, Kennedy, and Bittner (1986) suggested that ataxia is due to a disruption in balance and coordination resulting from the visual and vestibular adaptation to conflicting cues occurring during simulator exposure. In a study of Air Force pilots, Kellogg and Gillingham (1986) found that 60.4% reported ataxia shortly after simulator exposure. For 14.6% of the pilots, disequilibrium persisted as long as 30 minutes to 10 hours. Additionally, Fowlkes, Kennedy, and Lilienthal (1987) reported that it has been found that intensity and duration of ataxia increases with increased simulator exposure. Ataxia does not always result, however, (e.g., Kennedy, Allgood, et al., 1987) but this could be due to the exposure time or sensitivity of the postural test. It may also be that some simulators - such as those with motion platforms - may be more conducive to disequilibrium than others (motion platforms are discussed later in this report).

Baltzley, Kennedy, Berbaum, Lilienthal, and Gower (1989) investigated the issue of postflight symptoms. They reported that unsteadiness and ataxia are of greatest immediate concern for safety since there have been reports of such posteffects lasting longer than 6 hours and, in some cases, longer than 12 hours. In their study of free response data from 742 pilot exposures from 11 military simulators, they found that approximately half of the pilots (334) reported posteffects of some kind: 250 (34%) reported that symptoms dissipated in less than 1 hour, 44 (6%) reported that symptoms lasted longer than 4

hours, and 28 (4%) reported that symptoms lasted longer than 6 hours. There were also 4 (1%) reported cases of spontaneously occurring flashbacks. Since typical post-simulator duties and debriefing are not usually time-consuming, one hour is probably the longest period a pilot would ordinarily be expected to remain at the simulator site. Thus, longer-lasting aftereffects, especially those such as flashbacks and dizziness, pose a safety risk to both the pilots and to others.

Dark focus shifts

As discussed in the next section, a frequently used measure of simulator sickness is the Simulator Sickness Questionnaire (SSQ) or some variation of it. Surveys such as the SSQ are of a self-report nature and, thus, represent subjective measures of sickness. From a measurement standpoint, it may be desirable to also have some type of objective measure of sickness, such as a physiological measure. One such physiological measure, changes in dark focus, is discussed in this section. Additional measures are discussed later in this report.

Dark focus is the physiological resting position of accommodation. Accommodation is the process in which the ciliary muscles at the front of the eye tighten. This increases the curvature of the lens, making it fatter so that near objects can be brought into focus (Goldstein, 1989). Dark focus is the resting state of this process: the point of focus in the absence of effective visual stimulation (e.g., the dark) (Fowlkes, Kennedy, Hettinger, & Harm, 1993).

Accommodation is controlled by the autonomic nervous system (ANS). Motion sickness symptomatology is characteristic of the parasympathetic nervous system, a division of the ANS. Fowlkes et al. (1993) pointed out that increased parasympathetic activity results in an inward shift in dark focus and lens accommodation for near vision. They identified two important consequences of these changes. First, dark focus shifts may serve as an objective measure of the occurrence and severity of simulator sickness. Second, changes in dark focus may have adverse implications for visual performance during and immediately following exposure to virtual environments. For example, an inward shift in focus might render a VE user unable to successfully meet the accomodative demands of distant viewing necessary for detecting targets.

Fowlkes et al. (1993) examined the relationship between dark focus and simulator sickness. In their study of both college students and pilots, dark focus was measured before and after exposure to simulator sickness-inducing conditions (a projected motion scene for the students and a simulator flight for the pilots). Simulator sickness was measured with a questionnaire.

In two of their three experiments (one with students and one with pilots), Fowlkes et al. (1993) found that subjects who were sick usually had dark focus shifts inward, whereas subjects who were not sick usually had unchanged dark focus scores or shifts outward. These results were as predicted based on the increased parasympathetic activity associated with motion sickness. In their other experiment (also with pilots), they found different results: subjects who were sick usually had no change in dark focus, whereas subjects who were not sick usually had outward shifts. These results were not as predicted.

To reconcile the two results, Fowlkes et al. (1993) suggested that change in dark focus (using a continuous range from outward shift to no change to inward shift) is positively associated with severity of sickness (using a continuous range from low severity to high severity). The range of these changes in dark focus, however, depends upon the demands of the situation. Thus, for a low-demand situation (i.e., the first two experiments), as sickness severity ranges from low to high, change in dark focus ranges from no change to an inward shift. On the other hand, for a high-demand situation (i.e., the third experiment), as sickness severity ranges from low to high, change in dark focus ranges from an outward shift to no change.

From these three experiments, Fowlkes et al. (1993) concluded that the dark focus of accommodation can undergo systematic change due to simulator exposure. Furthermore, the nature of this change may depend on the performance demands of the situation and may be associated with the incidence of sickness (Fowlkes et al.).

Eye strain

One common effect of exposure to virtual environments is eye strain and related oculomotor problems. According to Stone (1993), two groups of British researchers found that only ten minutes spent wearing a HMD can result in side effects such as what might be observed after eight hours spent in front of a Cathode Ray Tube (CRT) display: headaches, nausea, and blurred vision, for example. Stone expressed concern over the strain imposed on binocular vision by HMDs. He pointed out that, whereas binocular vision is fully developed in adults, it is not fully developed in children under 12 and, thus, is more likely to break down under stress, causing squinting. It is Stone's opinion that the visual and motor system effects, although mostly anecdotal, are potentially serious, especially for lower quality VE systems such as those geared for entertainment. As Stone indicated, problems such as binocular convergence, inappropriate accommodative response to blurred images, unequal focusing capability in each eye, and inadequate fixation or pursuit eye movements are all evident in current Liquid Crystal Display (LCD)-based HMDs. These problems are known to contribute to a

disorder known as asthenopia, which Stone described as a type of oculomotor instability.

Ebenholtz (1992) also addressed the issue of asthenopia. He pointed out that it appears to result from the negative feedback control of most oculomotor systems. These systems, he stated, work to correct visual errors over a certain limited range, such as small differences in the direction in which the two eyes point. It is working to correct the errors, rather than the errors themselves, which appears to be problematic (Duke-Elder & Abrams, 1970). Thus, situations yielding error in eye movement control and involving the error-control mechanism have the potential to evoke symptoms of motion sickness (Ebenholtz).

Ebenholtz (1992) concluded that since the display devices of virtual environments, just like those in simulators, call on numerous oculomotor systems which may require error-correcting eye movements, they can potentially produce sickness symptoms. He noted that a prolonged need for error correction may result in adaptive shifts of the gain, phase, and direction of eye movements so that such error correction would no longer be necessary. Ebenholtz included such adaptive shifts among the possible effects of exposure to virtual environments. He further noted that such shifts may not be limited solely to the oculomotor system. He mentioned aftereffects such as ataxia and flashbacks as examples of other forms of adaptive shifts resulting from simulator exposure.

Performance changes

Kennedy, Fowlkes, and Lilienthal (1993) investigated performance changes following simulator exposure. Subjects were given three performance tests before and after simulator exposure: Pattern Comparison, Grammatical Reasoning, and Finger Tapping. The exposed pilots showed less improvement due to practice on the Pattern Comparison and Grammatical Reasoning tests than did the control group. Such differences were not observed on the Tapping test. Kennedy, Fowlkes, et al. noted that, of the three performance measures administered, Grammatical Reasoning is the most sensitive to disruption by stressors whereas Tapping is highly resistant to disruption. Although the results indicated minimal and unclear effects, Kennedy, Fowlkes, et al. nonetheless concluded that performance losses may occur following simulator exposure.

Quantitative Tools

Measuring simulator sickness: The Simulator Sickness Questionnaire

Questionnaires or symptom checklists are the usual means of measuring simulator sickness. This is because of the

polysymptomatic nature of the sickness: measuring just one sign or symptom would not be sensitive enough (Kennedy & Fowlkes, 1992). One frequently used questionnaire is the Pensacola Motion Sickness Questionnaire (MSQ) (Kellogg, Kennedy, & Graybiel, 1965). This questionnaire is a self-report form consisting of 23 symptoms which are rated by the subject on a 4-point severity scale (none, slight, moderate, severe). Although the multi-symptom scoring of the MSQ takes into account polysymptomaticity, a major deficiency for its application to the study of simulator sickness is that the single resultant score provides no information about the multiple, separable dimensions of the sickness (Kennedy & Fowlkes, 1992). This deficiency led to the development of the Simulator Sickness Questionnaire (SSQ) (Kennedy, Lane, Berbaum, & Lilienthal, 1993).

The SSQ was derived from the MSQ using factor analyses of 1,119 MSQs collected at 10 simulator sites. The resulting SSQ reduced the symptom list to 16 symptoms, which are rated by the subject on a 4-point scale (0=absent, 1=slight, 2=moderate, 3=severe). Based on the results of the factor analysis, these ratings form the basis for three subscale scores - Nausea, Oculomotor Discomfort, and Disorientation - as well as a Total Severity score. The symptoms making up the three subscale scores are as follows: Nausea - general discomfort, increased salivation, sweating, nausea, difficulty concentrating, stomach awareness, and burping; Oculomotor - general discomfort, fatigue, headache, eyestrain, difficulty focusing, difficulty concentrating, and blurred vision; and Disorientation - difficulty focusing, nausea, fullness of head, blurred vision, dizzy (eyes open), dizzy (eyes closed), and vertigo (Kennedy, Lane, et al., 1993). (Note that some symptoms appear on more than one subscale; this is a characteristic of the factor analysis procedure.) The Total Severity score uses all of the symptoms.

As is discussed later in this report, individuals who are not in their usual state of fitness (e.g., suffering from a cold or flu, hangover, etc.) tend to have an increased susceptibility to simulator sickness. Because of this, Kennedy, Lane, et al. (1993) advised that, in administering the SSQ, such individuals should not be included in the sample. Additionally, only post-exposure data are typically scored since there is a high correlation between pre- and post-exposure scores. These restrictions probably do not pose a problem with flight simulators because pilots form such a relatively homogeneous group - they tend to be in good physical shape overall and are usually in good health when they arrive for simulator training. However, because of the more diverse user population potentially associated with VE systems, military data may not be comparable to general population data, especially if different scoring systems are used. For instance, pre-exposure sickness scores may need to be considered in interpreting post-exposure scores.

Once SSQ scores are determined in a given situation, there are several ways the results can be used. Kennedy, Lane, et al. (1993) pointed out that the total severity factor may reflect the overall extent of symptom severity and, as such, provides the best index of whether a given simulator has a sickness problem. Additionally, the subscale scores can provide diagnostic information as to the specific nature of the resulting sickness (Kennedy, Lane, et al.). Thus, the data can be looked at on their own since all four scores have a natural zero (i.e., no symptoms) and increase in value as severity increases. Additionally, Kennedy, Lane, et al. supplied the original data so that, for new scores, percentile points can be determined (based on the original data) and means and standard deviations can be compared (to those of the original data). Lastly, scores in one situation can be compared to scores from other or similar situations (e.g. one simulator can be compared to another, or one simulator can be compared with itself at different points in time, such as prior to or following calibration adjustments).

Evaluating ataxia: Postural tests

Some studies (e.g., Baltzley et al., 1989, discussed earlier) have evaluated ataxia by means of free response survey data (i.e., self-report). Ataxia can also be measured with postural tests. Four of the basic tests are Stand-on-Preferred-Leg, Stand-on-Nonpreferred-Leg, Stand-Heel-to-Toe, and Walk-Heel-to-Toe. In each of these tests, the subject is instructed to either stand or walk in a specified manner for a specific amount of time or number of steps. The postural measure is the amount of time the subject is able to stand (up to the specified maximum) or the number of steps the subject is able to take (up to the specified maximum). Additional postural tests can be created from these basic four by adding such variations as eyes open vs. closed, arms outstretched vs. folded across chest, and different standing positions.

Thomley et al. (1986) evaluated the reliability of the four basic tests for repeated measurement of ataxia. They studied the tests under baseline conditions: before and after playing approximately 30 minutes of video games. The use of the games was for other experimental purposes and was not expected to have postural effects. For all tests, subjects had arms crossed and eyes closed. Based on an analysis of means and variances, as well as a correlational analysis, Thomley et al. recommended a Stand-on-Leg test with the Stand-on-Nonpreferred-Leg being marginally superior to the Stand-on-Preferred-Leg. It should be noted that ceiling effects were seen on all four tests, even from the first trial, and that such postural tests typically exhibit learning effects (i.e., performance improves with practice).

Hamilton, Kantor, and Magee (1989) also evaluated several ataxia tests to determine their sensitivities and reliabilities.

They studied four variations of the basic tests: the Sharpened Romberg (also called the Tandem Romberg), Stand-on-One-Leg-Eyes-Closed, Walk-on-Rail-Eyes-Open, and Walk-on-Line-Eyes-Closed tests. In the Sharpened Romberg, subjects stand heel-to-toe with arms folded and eyes closed. Hamilton et al. modified the Sharpened Romberg and had subjects walk on narrow rails to increase the difficulty in an attempt to avoid ceiling effects.

In the first phase of the two-phase study, test-retest reliabilities were examined. It was found that the reliability coefficients for each test remained relatively stable. Although learning effects were found, ceiling effects were not. The Stand-on-One-Leg-Eyes-Closed was found to be the most reliable, but only the Stand-on-One-Leg-Eyes-Closed and the Sharpened Romberg reliabilities exceeded .50.

In the second phase of the study, the first phase subjects performed each of the four tests immediately before and after two successive 6-minute flight simulator exposures. In addition, each subject completed a simulator sickness questionnaire. It was found that, despite subject reports of ataxia symptoms following the simulator exposure, only the Sharpened Romberg substantiated the symptoms reported on the questionnaires. Hamilton et al. (1989) concluded that none of the four tests were sensitive enough to quantify subjective reports of ataxia and that more sensitive measures are needed. In fact, because of the ceiling effects and only moderate reliabilities of such postural measures, Thomley et al. (1986) suggested that alternative measures, such as head stability-assessment devices be developed. The position-tracker in an HMD may be one such method for assessing head stability.

Predicting simulator sickness: The Motion Sickness History Questionnaire

Kennedy, Fowlkes, et al. (1992) noted that motion history questionnaires are useful tools for predicting many forms of motion sickness. Such questionnaires have high retest reliabilities with low cost for materials and little inconvenience for the subject (Kennedy, Fowlkes, et al.). Use of these motion history questionnaires for the prediction of simulator sickness, however, has not been as successful. Thus, Kennedy, Fowlkes, et al. investigated the use of questionnaires to predict simulator sickness specifically.

The motion history questionnaire employed by Kennedy, Fowlkes, et al. (1992) was the Kennedy and Graybiel version of the Pensacola Motion Sickness Questionnaire (used for the development of the SSQ), referred to as the Motion History Questionnaire (MHQ). Four different scoring keys were developed based on different combinations of items from the MHQ (see Kennedy, Fowlkes, et al. for the specific MHQ items included in

each of the four scoring keys). The first scoring key - the original scoring key for the MHQ - had been validated on a sample of student pilots exposed to Coriolis forces. Coriolis stimulation is experienced when the body is being rotated and the head is tilted out of the axis of rotation (Dichgans & Brandt, 1973; Guedry & Montague, 1961). Similarly, pseudo-Coriolis stimulation is experienced when the head is tilted during illusory self-rotation induced by moving visual stimuli (Dichgans & Brandt, 1973). In a preliminary study with a small sample, the MHQ - as scored with the original key - did not correlate significantly with the reported sickness symptomatology (Kennedy, Fowlkes, et al., 1992). Thus, two additional scoring keys were later developed. These scoring keys had been validated on a sample of college students exposed to highly provocative and mildly provocative simulated ship motion (VLF vibration). The fourth scoring key, the simulator sickness scoring key (SS), was empirically derived and cross-validated as part of the study.

The goal of this research was to compare the original MHQ scoring key, the VLF scoring keys, and the empirically derived SS scoring key in terms of their relative predictive abilities for simulator sickness susceptibility. Two dependent variables were used in the study: a score on the MHQ taken after simulator exposure (POST) and the difference between scores on the MHQ taken before and after simulator exposure (DIFF). The SS scoring key was developed by examining the correlation of each of the individual items of the MHQ with both the POST and DIFF scores. If the correlation for POST, DIFF, or both was significant at the 0.05 level, that MHQ item was included in the SS scoring key. To compare the four scoring keys, correlations between the four scoring keys and the two dependent variables were examined. All of the scoring keys were found to be predictive of reported symptoms of simulator sickness, but the highest correlations (.33 for both dependent variables) were obtained with the SS key.

Factors Associated with the Individual

There are very large individual differences in susceptibility to simulator sickness. Such individual difference factors include age, concentration level, ethnicity, experience with the real-world task, experience with the simulator (adaptation), the flicker fusion frequency threshold, gender, illness and personal characteristics, mental rotation ability, perceptual style, and postural stability. These factors are all discussed below.

Age

One source of individual differences is age. Reason and Brand (1975) reported that motion sickness susceptibility is greatest between the ages of 2 to approximately 12 years. It

decreases rapidly from about 12 to 21 years and then more slowly thereafter. After around 50, sickness is almost nonexistent.

Related to age is experience with the real-world task, which plays a critical role in the cue conflict theory of simulator sickness: conflicts are thought to occur between the actual pattern of stimuli and the expected pattern of stimuli. The expected patterns likely result from repeated experiences, which Reason and Brand (1975) suggest may follow the same long-term learning pattern seen with other types of learning. Age and experience are correlated and, as is discussed later in this section, experience with the real-world task is positively correlated with sickness.

Concentration level

Regan (1993) observed that higher levels of concentration may be associated with lower levels of sickness. Without any formal measurement of concentration level, she observed that some subjects need to concentrate more than others while in the VE, especially when picking up and manipulating objects with the 3D mouse.

Ethnicity

Stern, Hu, LeBlanc, and Koch (1993) compared susceptibility to visually-induced motion sickness among different ethnic groups. The subjects, all female, formed three groups: Chinese, European-American, and African-American (the Chinese were born in China, as opposed to the other two groups which were born in the United States). A circular vection drum was used to induce vection (illusory self-motion, discussed later in this report) while electrogastrography (EGG) signals were measured and subjective symptoms of motion sickness were noted as they were volunteered. It was found that the Chinese group reported significantly more nausea and other symptoms of motion sickness than either of the other two groups, which did not differ in their reports. A similar result was seen with the EGG signals during the drum rotation period. These results support the researchers' hypothesis that Chinese women are hyper-susceptible to motion sickness when compared with European-American and Afro-American women - a hypothesis which they developed from observations of subjects in their laboratory. Two theories were put forth to explain the differences obtained in the experiment: environmental factors (all of the Chinese subjects had been in the USA for less than 3 years) and genetic differences in central catecholamine release.

Experience with the real-world task

Based on findings in the field dating back to 1957, Kennedy, Berbaum, Lilienthal, Dunlap, Mulligan, and Funaro (1987) stated

that pilots with more flight experience and little simulator time are more prone to simulator sickness than are those with little aircraft flight time. Although the relationship is often observed, this finding is not fully consistent in the literature (Kennedy et al., 1988). Kennedy et al. (1988) suggested that, for the cases in which such a relationship is observed, the pilot's experience with the sensory aspects of actual flight might lead to greater sensitivity to the discrepancies between actual and simulated flight. Pausch, Crea, and Conway (1992) offered two other possible explanations. Degree of control of the task may be a factor since student pilots tend to handle the flight controls more than the instructor pilots. Second, viewing region may be a factor if the optimal viewing position is placed at the student's location. Both of these factors are discussed later in this report for their possible role in sickness. For the cases in which a positive relationship between experience and sickness is not observed, Kennedy et al. (1988) suggested that the pilot's experience may result in protection through some mechanism of adaptation or that susceptible individuals may have been self-selected out of a career in aviation.

Experience with the simulator (adaptation)

Uliano, Lambert, Kennedy, & Sheppard, (1986) found that pilots who experienced sickness on initial simulator hops were able to rapidly adapt to the simulator on following hops and, therefore, experienced less sickness over time. Thus, increased experience with the simulator - adaptation - generally leads to a decreased incidence of sickness. This could be the result of building a tolerance to sickness-inducing stimuli and learning adaptive behaviors to avoid sickness. Although this adaptation may help reduce sickness, Kennedy and Frank (1983) pointed out that it may cause problems when the individual returns to the normal environment. Similarly, Regan (1993) suggested that repeated immersions in a VE system will result in a decrease in sickness as subjects become more accustomed to, and confident about, interaction with the system. She added that it has been suggested that adaptation may lead to reduced symptoms during immersion, but greater levels of post-immersion symptoms.

Flicker fusion frequency threshold

Flicker is discussed in the next section for its role in sickness and all of the issues raised are properties of the display device. There is, however, another issue associated with flicker which is a property of the individual: the flicker fusion frequency threshold. This threshold is defined as the point at which flicker becomes visually perceptible. Grandjean (1988) indicated that the human flicker fusion frequency threshold is a circadian bodily function which increases by day and decreases by night. Thus, the threshold frequency at which flicker is detectable is reduced at night. In addition, there is

wide individual variability in the threshold along many dimensions such as gender, age, and intelligence (e.g., Botwinick & Brinley, 1963; Maxwell, 1992; Wilson, 1963).

Gender

Biocca (1992) reported that men and women do not differ in their sensory response to motion stimuli, yet women tend to be more susceptible to motion sickness. He pointed out that this may be due to underreporting of susceptibility by men in self-reports, but added that research has shown hormonal effects. For instance, susceptibility may change during pregnancy and menstruation. Kennedy and Frank (1983), however, noted that women exhibit larger fields of view than men and, as is discussed later in this report, wide fields of view tend to result in increased incidence of simulator sickness.

Illness and personal characteristics

Illness has also been identified as a potential factor related to simulator sickness susceptibility. Kennedy, Berbaum, et al. (1987) advised against simulator exposure for subjects who are not in their usual state of fitness and Kennedy, Lane, et al. (1993) advised that only individuals in their usual state of fitness should be included in the sample when administering the SSQ. This includes subjects who are suffering from fatigue, sleep loss, hangover, upset stomach, emotional stress, head colds, ear infection, ear blocks, upper respiratory illness, or the flu; as well as those taking certain medications or having just received a flu shot. Additionally, Biocca (1992) suggested that personal characteristics such as neuroticism, anxiety, arousal, and introversion may be related to sickness susceptibility. The exact nature of those effects, however, requires further research.

Mental rotation ability

Parker and Harm (1992) discussed the ability to mentally rotate objects and the possible role of this ability on VE sickness. Mental rotation is what a person must do in order to be able to recognize objects when they are not in their usual orientations. Parker and Harm's work is discussed in terms of a microgravity environment but they argue that since a VE, like microgravity, produces stimulus rearrangements, the results are applicable to virtual environments as well. They defined stimulus rearrangements as alterations or disturbances of the normal spatial relationships among stimuli that contribute to orientation. Such a rearrangement may occur when, for example, a subject "walks" forward in a virtual environment while remaining still in the real environment. Thus, stimulus rearrangements set the stage for cue conflicts.

Parker and Harm (1992) stated that mental rotation is important for efficient goal-directed locomotion - a common task in a VE - since a person must orient in order to locomote efficiently. They cited several examples which support their claim that the ability to perform mental rotation is important for competent function and the reduction of motion sickness.

The first study involved cosmonauts during a Soviet space mission. These cosmonauts were trained in a mental rotation procedure prior to flight and, during the mission, they significantly improved their performance on the procedure. Parker and Harm (1992) argued that, during the mission, the cosmonauts learned to locomote in their microgravity environment, a task which required mental rotation ability. They suggested that by improving their performance on this complex task, performance on the easier mental rotation procedure was also improved.

As a second piece of supporting evidence for their theory, Parker and Harm (1992) pointed out that different astronauts appear to have different methods of dealing with the sensory disturbances experienced in microgravity. Astronauts who appear to deal with the absence of gravity by paying more attention to internally-generated orientation vectors - especially the one associated with their Z-body axis (up-down) - are termed Type IZ. Parker and Harm suggested that these astronauts, who generally report little or no motion sickness during their space flights, are able to ignore visual cues for upright. They have conducted their own research on the matter of mental rotation and space motion sickness using the Device for Orientation and Motion Environments Preflight Adaptation Trainer (DOME-PAT), a microgravity simulator.

These results have several implications for virtual environments (Parker & Harm, 1992). First, mental rotation tests could be employed to identify individuals who may be less likely to experience sickness in virtual environments. As an alternative, VE users could receive training to improve their mental rotation abilities. For example, a VE system could be adapted to produce stimulus rearrangements, thus allowing users to practice mental rotations. Lastly, mental rotation skills learned in one virtual environment will likely transfer to other virtual environments.

Perceptual style

The field-dependence/independence dimension of cognitive style, commonly referred to as perceptual style, has been well represented in the literature. Classification of perceptual style is an indicator of the extent to which a surrounding field affects an individual's perception of an item within the field

or, in other words, the extent to which an individual perceives analytically (Witkin, Moore, Goodenough, & Cox, 1977).

Several tests can be used to classify an individual's perceptual style. The classical one is the Rod and Frame Test (RFT). This test measures the accuracy with which an individual can adjust a rod to the true vertical position under conditions of visual-kinesthetic conflict. Another test of perceptual style is the Embedded Figures Test (EFT), which measures the subject's ability to extract a geometric pattern from a complex pattern. Based on performance on tests such as these, an individual's perceptual style is classified as either field-independent or field-dependent. "Field-independent" individuals are able to perceive items as separate from a surrounding field - such individuals are able to adjust the rod to its true vertical with high accuracy and can successfully extract geometric patterns from the complex patterns. The perception of "field-dependent" individuals, however, is strongly dominated by the surrounding field - such individuals are unable to accurately adjust the rod to its true vertical and have difficulty discerning geometric patterns from complex patterns.

It has been suggested that field-independent individuals are more sensitive to body cues than are field-dependent individuals (Barrett & Thornton, 1968). Because of this sensitivity and the conflict between static body cues and dynamic visual cues in a moving display, field-independent individuals have been predicted to be more susceptible to simulator sickness than field-dependent individuals (Barrett & Thornton, 1968).

Barrett and Thornton (1968) and Barrett, Thornton, and Cabe (1969, 1970) investigated the possible relationship between perceptual style and simulator sickness. Barrett and Thornton (1968) found that all of the extremely field-independent subjects left the simulator and, even though some field-dependent subjects also became ill in the simulator, they concluded that the results supported their prediction that field-independent individuals would experience more discomfort. Barrett, Thornton, and Cabe (1969), however, found no relationship between simulator sickness and perceptual style as measured with the EFT. Barrett, Thornton, and Cabe (1970) investigated the relationship between perceptual style and cue conflict induced by a "haunted swing"-like device. The results indicated that, although many subjects did experience discomfort in the swing, it was the field-dependent individuals who experienced the most discomfort - opposite the Barrett and Thornton hypothesis.

Although there would be great theoretical and practical value if a predictive relationship could be found between perceptual-style and susceptibility to motion sickness (Long, Ambler, & Guedry, 1975), the only clear result that can be discerned from these studies is that there is no clear result.

Frank and Casali (1986) reviewed additional studies examining the relationship between perceptual style and simulator sickness. They also concluded that little convincing evidence exists to support the theory that field-independent individuals are more susceptible than field dependent-individuals. As they pointed out, perhaps perceptual style is unrelated to simulator sickness susceptibility!

Several points can be made about the perceptual style literature. Frank and Casali (1986) noted that, in order for perceptual style to be a meaningful predictor, the entire range of the perceptual style continuum must be considered. Many studies, however, focus only on the extremes of field independence and dependence. In addition, Ebenholtz (1977) suggested that the visual system of field-dependent subjects may be peripheral-dominant whereas the visual system of field-independent subjects may be foveal-dominant. Since the periphery is more sensitive to motion and since the perception of motion in the periphery may induce vection, this would imply that field-dependent subjects would be more likely to experience a conflict between visual and proprioceptive stimuli. By this reasoning, field-dependent individuals should be more susceptible to simulator sickness. Clearly, the relationship between perceptual style and simulator sickness, if one exists, is not an obvious one.

Postural stability

As was discussed earlier in this report, postural instability - ataxia - is a well documented effect of simulator exposure. Postural stability is often measured before and after simulator exposure to determine decrements in stability due to exposure. Based on available literature, it does not appear that postural stability has ever been used as a predictor of simulator sickness. Recent research, however, suggests that there may be a relationship between pre-simulator postural stability and post-simulator sickness (Kolasinski, Jones, Kennedy, & Gilson, 1994).

Kolasinski et al. (1994) hypothesized that individuals who are less posturally stable will be more likely to experience simulator sickness or will experience more severe sickness; conversely, individuals who are more posturally stable will be less likely to experience simulator sickness or will experience less severe sickness. To investigate this hypothesis, pre-simulator postural stability and post-simulator sickness data from Navy helicopter pilots were analyzed. It was found that pre-simulator postural stability was most strongly associated with the Nausea and Disorientation subscale scores on the SSQ. Postural stability did not appear to be associated with the Oculomotor subscale score. This result complements previous results which have shown that poor post-simulator postural

stability is related to high Disorientation subscale scores (Jones, Kennedy, Lilienthal, & Berbaum, 1993).

At the very least, the existence of a relationship between pre-simulator postural stability and post-simulator sickness could shed light on the mechanism controlling simulator sickness. Furthermore, it would provide support for the use of postural tests as predictors of simulator sickness susceptibility. It could, however, have specific implications for liability issues concerned with public-use virtual reality systems. Decreased postural stability for a given individual might be indicative of illness, drugs, or alcohol. It is highly likely that individuals in such states would be more likely to experience sickness, especially with lower-quality commercial VR systems. Thus, some specified level of postural stability could be used as a requirement before an individual would be permitted to use those systems.

Factors Associated with the Simulator

Jones (1993) implied that the one sure way to eliminate visually-induced motion sickness is to shut off the visual system. Distorted graphics, visual lags, and off-axis viewing are just some of the many aspects of the visual display which could be problematic (Kennedy et al., 1988). Pausch et al. (1992) provided an in-depth review of the literature concerning technical properties of the simulator - specifically, those associated with the visual display - which may correlate with sickness. They identified time lag, phosphor lag, refresh rate, and update rate as potentially the most important aspects of a simulation system, yet among the most difficult to measure. Other factors they discussed which may influence sickness are contrast, resolution, color, field of view, viewing region, binocular viewing, scene content, and flicker. These are all discussed in detail below. In addition to these features of the visual display, other features of the simulator, such as calibration, inter-pupillary distance in head-mounted displays, motion platforms, and position-tracking error may be associated with sickness and are also discussed.

Binocular viewing

Humans can view a display in one of several ways depending on both the human and the display. First, either one eye or both eyes can be used. The former can be termed monocular viewing and the latter binocular viewing. A binocular display, such as an HMD, can present identical or different images to each eye. The former is referred to as a monoscopic display and the latter, a stereoscopic display. Whereas a monoscopic display can provide depth cues such as relative size and overlap, a stereoscopic display permits depth perception based on binocular cues (stereopsis). Although monocular cues are adequate for many

tasks, it is widely believed that depth perception is much enhanced when binocular depth cues can be used (Levine & Shefner, 1991). Arditi (1986), however, noted that stereopsis is not necessary for valid depth perception. This is fortunate, perhaps, because, as Pausch et al. (1992) noted, it is difficult to build a system which allows for true binocular vision since binocular depth cues are difficult to simulate.

Recent ARI research compared performance between monoscopic and stereoscopic displays (Ehrlich, Singer, & Cinq-Mars, S., in preparation). Ehrlich et al. also measured simulator sickness with the SSQ. Based on previous results, it was hypothesized that increased sickness would be observed in users of the stereoscopic display. Indeed, it was found that the mean score on the Nausea subscale was significantly higher with the stereoscopic presentation than with the monoscopic presentation. This result, however, did not hold true for the other SSQ sickness scores.

Calibration

McCauley and Sharkey (1992) discussed some reasons why sickness will probably be more prevalent in virtual environments than in military flight simulators. They pointed out that commercial VE systems will probably not benefit from the regular calibration that military flight simulators typically receive. Lack of calibration could result in increased spatial and temporal distortions which could set the stage for sickness due to distorted graphics.

Color

Color is detected by the foveal visual system, whereas motion is largely detected by the peripheral system (Levine & Shefner, 1991). Thus, because of the role of motion detection in simulator sickness, color is not likely to be a factor in simulator sickness. However, color displays may have lower resolution (Pausch et al., 1992) and resolution is discussed later in this section as a possible factor in sickness. Thus, any role of color in simulator sickness is most likely to be indirect, stemming from the possible trade-off between the use of color and display resolution.

Contrast

Contrast may be defined as the ratio of the highest luminance provided by the display to the lowest (Pausch et al., 1992). It is also related to resolution and, for low luminance ranges, any adjustment of either luminance, contrast, or resolution may require adjustment of the other two in order to achieve a proper visual display (Pausch et al.). At higher luminances, these tradeoffs are not as great unless contrast and

resolution are very poor. Luminance level, however, is related to flicker. Flicker is believed to be associated with simulator sickness and is discussed later in this section. Thus, any role of contrast in simulator sickness is most likely to be through its indirect relationship to flicker.

Field of view

Field-of-view is defined as the horizontal and vertical angular dimensions of the display (Pausch et al., 1992). Simulators with a wide field-of-view generally exhibit higher incidences of simulator sickness than do those with a narrow field-of-view (Kennedy et al., 1989). This is likely due to increased vection arising from increased stimulation of the peripheral retina from a wide field-of-view display (Kennedy et al., 1988). Vection plays an important role in simulator sickness and is discussed in the next section. Anderson and Braunstein (1985), however, induced vection using only a small portion of the central visual field with stimuli which appeared to have depth. This led them to conclude that the representation of motion and texture cues in the display may actually be more critical than the display's field-of-view.

A wide field-of-view also increases the likelihood that flicker will be perceived (Maxwell, 1992). This is because the peripheral visual system is more sensitive to flicker than is the fovea (Boff & Lincoln, 1988). Thus, if flicker is to be avoided, a wider field-of-view necessitates a faster refresh rate (Maxwell).

Flicker

Flicker has been extensively studied. The interested reader can find a review of primarily recent references on flicker perception and simulator sickness in the annotated bibliography by Rinalducci and MacArthur (1990).

The extensive literature concerning flicker reveals that flicker is something to be avoided if at all possible since it is distracting, induces eye fatigue, and appears to be associated with simulator sickness (e.g., Harwood & Foley, 1987; Pausch et al., 1992; Rinalducci & MacArthur). The perception of flicker differs among individuals and depends on an individual's flicker fusion frequency threshold, as discussed in the previous section.

Several aspects of the visual display affect the perception of flicker. Of these aspects, those most applicable to the visual displays of virtual reality systems are refresh rate, luminance level, and field-of-view (e.g., Boff & Lincoln, 1988; Farrell, Casson, Haynie, & Benson, 1988; Maxwell, 1992). In order to suppress flicker, refresh rate must increase as the luminance level increases (Farrell et al.). Refresh rate must

also increase as field-of-view increases, since a large field-of-view increases the likelihood that flicker will be perceived (Maxwell). This is due to the fact that the peripheral visual system is more sensitive to flicker than is the fovea (Boff & Lincoln, 1988).

Thus, in selecting a visual display, several trade-offs are necessary. In order to suppress flicker, refresh rate must increase as both luminance level and field-of-view increase. However, displays with faster refresh rates cost more. Thus, slower refresh rates may be employed in an effort to keep costs down. Slower refresh rates, however, promote flicker and require more persistent phosphors. But long-persistence phosphors promote phosphor lag, which may lead to disturbing smeared images (Pausch et al., 1992). Trade-offs can also be made with luminance specifications and this is discussed in the next section.

Inter-pupillary distance

Typical LCDs in a head-mounted display are a fixed distance apart. In light of this, Regan and Price (1993) hypothesized that if a subject has an inter-pupillary distance which is markedly greater or smaller than the system configuration, potential eyestrain, headaches, and associated visual system problems may result. For a group of 53 subjects as a whole, this hypothesis was not supported. However, when only subjects with an inter-pupillary distance less than the system configuration (which was the majority of the subjects) were considered, there was some suggestion that the subjects who had the greater deviations from the system configuration were those who experienced ocular problems. Considering only those individuals does have some basis. Diverging one's eyes is likely to cause greater ocular stress than would converging. Individuals with an inter-pupillary distance less than the system configuration would have to diverge their eyes to conform to the system. Thus, considering this reduced group may be appropriate to identify visual system problems resulting from the fixed inter-pupillary distance. Despite the somewhat muddy results, Regan and Price concluded that the fixed inter-pupillary distance in HMDs may play a role in ocular discomfort.

Motion platform

Motion was added to early driving simulators in an attempt to reduce cue conflict (Casali, 1986). Sickness, however, still occurred. Kennedy, Allgood, et al. (1987) noted that this sickness may actually be true motion sickness. With a motion platform, however, conflicts between visual and motion cues are possible and these conflicts could lead to sickness (Casali, 1986). In addition, Kennedy, Fowlkes, et al. (1993) noted that motion bases may also aggravate the problem of ataxia, especially

during very long simulator exposures, due to adaptive changes in postural control.

Despite the possibility that motion bases may cause motion sickness and may result in increased ataxia, a motion base is still considered by many to be a cure for conflict between the visual and vestibular systems. Sharkey and McCauley (1992) addressed this issue and concluded that, despite the intuitive appeal of this belief, a motion base is not an engineering solution to the sickness issue. They conducted their research using the NASA-Ames Research Center's Vertical Motion Simulator (VMS), the world's largest motion-base simulator. In their study, pilots experienced motion sickness in the motion-base condition equal to that experienced in the fixed-base condition. In an analysis of their results, they noted three important considerations related to this finding. First, a power analysis convinced them that their measures were sensitive enough to detect meaningful differences if such existed. Second, since it is unlikely that the motion-cuing capabilities of future flight trainers will be significantly greater than those of the VMS, if the VMS can not reduce cue conflict, future trainers probably will not be able to either. Lastly, sickness in the motion-base condition and sickness in the fixed-base condition may have had different causes. In the fixed-base condition, sickness may have been due to the lack of motion, whereas in the motion-base condition, it could have been due to washout. In such a system, there are limits which define the simulator's range of motion. Motion washout is an acceleration applied to the simulator cab to keep it from approaching those system limits or to return it to the center of its range of motion (Sharkey & McCauley). They noted that this acceleration may produce false motion cues which may have interacted with the simulated motion cues, thus producing sickness.

Sharkey and McCauley (1992) concluded that if the system features of even the VMS are not enough to eliminate cue conflict, then perhaps efforts should be spent on issues other than motion bases. McCauley and Sharkey (1992) suggested that less expensive alternatives to motion-bases, such as vibration seats, might provide sufficient "noise" to the vestibular and proprioceptive senses to reduce the conflict with the visually implied motion. However, simple random vibration alone was not enough to alleviate sickness in driving simulators (Casali, 1986).

Phosphor lag

Phosphor lag is defined as the continued glowing of the phosphor on the CRT screen from one frame to the next (Pausch et al., 1992). Excessive phosphor lag causes smearing of a moving image and, possibly, visible after-images of previous frames.

These distorted images may be disturbing and may contribute to simulator sickness (Pausch et al.).

Position-tracking error

Biocca (1992) discussed the possible effect of position-tracking error on sickness. The position-tracker in a VE system provides the computer with information about the location of the user's head and, possibly, limbs in space. This information is used by the system to construct a graphical representation of the user inside the VE. If this information is in error, tracked objects may appear to be places they are not. If these tracked objects are part of the user's body, the user may be disturbed by the discrepancy between where the graphical representations of the objects appear in the visual display and where the user thinks they should appear. The result may be a breakdown of the illusion of the simulation, possibly resulting in sickness-related symptoms such as dizziness and lack of concentration (Biocca).

Position-tracking errors, therefore, create a form of cue conflict. Biocca identified three kinds of conflicts. The first conflict occurs between a visually represented limb and the felt position of the limb. Slight discrepancies are unlikely to disturb users, but conflicts between visually represented and felt positions may vary depending on the location of the user in the virtual space. This space, as calculated by the current technology of position trackers, is often slightly distorted. Thus, large, potentially disturbing, discrepancies are possible.

The second conflict occurs due to lags in updating body, limb, or head position. This conflict occurs when users move their head or limbs and their view of the VE drags noticeably behind. In such instances, users may minimize movements such as rapid head turning and tilting in order reduce the period between motion input and motion output.

Lastly, position-tracking errors may also cause jitter or oscillations of represented body parts and users may find this unsettling. A result by Hettinger, Berbaum, Kennedy, Dunlap, and Nolan (1990) indicated that visual or physical oscillation in the range of 0.2-0.25 Hz may be the most nauseogenic.

Refresh rate

Refresh rate is defined as the frequency with which the CRT's electron beam relights the phosphor pixels (Thorell & Smith, 1990). Slow refresh rates promote flicker and may lead to phosphor lag, both of which may be associated with sickness (Pausch et al., 1992), as discussed earlier in this report. Furthermore, refresh rate combines with both field-of-view and luminance level in their effect on flicker (Pausch et al., 1992).

To avoid flicker, refresh rate must increase as both field-of-view and luminance level increase (Farrell et al., 1988; Maxwell, 1992). At high refresh rates, luminance can be any level, but displays with faster refresh rates cost more. Thus, if faster refresh is not an option, dusk conditions (i.e., lower luminance) may be simulated in a system with a slower refresh rate in order to prevent flicker.

Resolution

Resolution is a measure of the level of detail provided by the display and is related to both contrast and luminance level (Pausch et al., 1992). As with contrast, any adjustment of one may require adjustment of the other two in order to achieve a proper visual display, especially at lower luminance ranges. At higher luminances, these tradeoffs are not as great unless resolution and contrast are very poor. Luminance level, however, is related to flicker, which is associated with sickness and was discussed earlier in this section. Thus, resolution's role in simulator sickness is most likely to be indirect, stemming from the relationship to flicker.

Scene content

Scene content is defined as the level of detail available for a given scene (Pausch et. al, 1992). It affects update rate, which is discussed later in this section for its role in simulator sickness. Any association between scene content and sickness is probably indirect, through the effect of scene content on update rate.

Time lag (transport delay)

Time lag, also known as transport delay, can be associated with the motion or visual system. It refers to the delay between information input to and motion or visual output from the simulator (Pausch et al., 1992). A driving simulator study by Frank, Casali, and Wierwille (1988) concluded that visual lag is more disruptive to both a user's performance and comfort than is motion lag. Large lag may lead to conflict among cues from the different simulator systems (e.g., motion, visual, and instrument) (Pausch et al.).

Uliano et al. (1986), however, found no effect of visual lag on sickness even though long lags were somewhat disruptive to performance. They caution against generalizing their results, however, on two grounds. First, the pilots in their study performed only two tasks, which had been selected because of their nauseogenic properties. Second, because the system was fixed-base, there was no lag possible between visual and motion cues. Nevertheless, Uliano et al. concluded that visual lag

asynchrony - within the limits studied in their research - is probably not a contributing factor to simulator sickness.

Update rate (frame rate)

Update rate, also referred to as frame rate, is defined as the speed of the simulation: the rate at which subsequent frames of the moving scene can be generated and rendered into the frame buffer for display (Pausch et al., 1992). Unlike the hardware-determined refresh rate, it can vary widely based on scene complexity and available computing power for the simulation (Pausch et al.). A slow update rate could lead to visual lag, which may be associated with sickness. Thus, any effect of update rate on sickness is likely to be indirect and due to its effect on other aspects of the simulation.

Viewing region

Pausch et al. (1992) defined viewing region as the volume in front of the display where an observer can be situated and still see an undistorted, high-quality view of the simulated scene. The optimal position for the observer is called the design eyepoint and is located in the center of the viewing region. Moving away from the design eyepoint increases image distortion. Outside the viewing region of infinity-focused optics, the graphics disappear or become of unacceptable quality. Pausch et al. stated that the effect of this small optimal viewing region is that some simulator users may be far away from the design eyepoint even though they are still inside the viewing region. Thus, simulator sickness incidence and ataxia for these users may increase due to distorted visuals. This may be one explanation for the different sickness incidence rates observed among different crew members (Casali & Wierwille, 1986). Some crew members, such as pilots, may be located at or closer to the design eyepoint; whereas other crew members, such as co-pilots, although still inside the viewing region, may be located away from the design eyepoint.

Factors Associated with the Simulated Task

Several features of the particular task being simulated may be associated with sickness. These factors are likely to differ from task to task and may include such things as altitude above the terrain, degree of control, duration, global visual flow, head movements, luminance level, method of movement, rate of linear or rotational acceleration, self-movement speed, sitting vs. standing, type of application, unusual maneuvers, and vection. These are all discussed below.

Altitude above the terrain

Kennedy, Berbaum, & Smith (1993) noted that altitude has been found to be one of the strongest contributors to sickness. Altitude is related to global visual flow (discussed later in this section). At low altitudes, the visual flow cues indicating movement are greater than those at high altitudes. To minimize sickness during flying tasks, McCauley and Sharkey (1992) recommended that self-movement in a VE should be at high altitudes above the terrain.

Degree of control

Sickness incidence is often less for pilots and drivers than for co-pilots and "passengers" (Casali, 1986). These observations may be explained in part by results such as those of Casali and Wierwille (1986), who noted that simulator sickness susceptibility among aircrews can be a function of the member's degree of control in the simulator cockpit. Pilots, as Pausch et al. (1992) pointed out, generally control more of the motion and visuals than do other flight crew members. Similarly, Pausch et al. reported that previous results have found that subjects who generated input themselves were less susceptible to motion sickness. This is likely because controlling allows one to anticipate future motion so that any possible cue conflict can be reduced or eliminated.

Duration

It was stated earlier that intensity and duration of ataxia increases with increased simulator exposure (Fowlkes et al., 1987). McCauley and Sharkey (1992) also suggested that longer exposure times to virtual environments will result in an increased incidence of sickness and will require longer adaptation periods. Furthermore, as was discussed earlier, there appears to be an effect of motion bases on ataxia during very long simulator exposures (Kennedy, Fowlkes, et al., 1993). As was noted earlier, this is likely due to disruptions in normal postural control.

Global visual flow

Global visual flow is defined as the rate at which objects flow through the visual scene (McCauley & Sharkey, 1992). Maximum global visual flow rate is the observer's velocity divided by the observer's eyeheight above the terrain surface (Owen, 1990). It has a value of zero for images at the horizon. Thus, global visual flow is directly related to velocity and inversely related to altitude and visual range. As was mentioned earlier, altitude has been found to be one of the strongest contributors to sickness (Kennedy, Berbaum, et al., 1993). To reduce sickness by minimizing global visual flow, McCauley and

Sharkey recommended that self-movement in a virtual environment should be at high altitudes above the terrain and/or at low speeds.

Head movements

Reason and Brand (1975) stated that a significant reduction in motion sickness occurs when an individual adopts a supine position. They attributed this to restricted motion of the head. Head motions are known to be associated with motion sickness through the mechanisms of Coriolis and pseudo-Coriolis stimulation. Coriolis stimulation occurs when the head is tilted out of the axis of rotation during actual body rotation (Dichgans & Brandt, 1973; Guedry & Montague, 1961). Pseudo-Coriolis stimulation occurs when the head is tilted as perceived self-rotation is induced from visual stimuli (Dichgans & Brandt, 1973).

During her study of the frequency of occurrence and severity of sickness in virtual environments, Regan (1993) noted that some subjects moved more slowly and cautiously through the VE and made fewer head movements than others. To investigate this matter further, another study was conducted in which two groups of subjects were compared (Regan, 1993). One group underwent actions in the VE which were designed to maximize head movements and speed of interaction with the system. These subjects were compared to subjects in an earlier study who controlled their own head movements and speed of interaction. VE exposure for the first group lasted 10 minutes and, for the control group, only the first 10 minutes of their VE exposures were analyzed. In the experimental condition, 50% of the subjects reported ratings greater than 1 whereas, in the control group, only 36% of the subjects reported ratings greater than 1 (Regan's rating scale is discussed earlier in this report). Since mean ratings for the two groups did not differ significantly, Regan concluded that some factor other than head movement and speed must have been responsible for the level of side-effects reported.

Luminance level

Luminance is defined as the intensity or brightness of the light coming from the display and is related to both contrast and resolution (Pausch et al., 1992). Thus, any adjustment of one may require adjustment of the other two in order to achieve a proper visual display, especially at lower luminance levels (Pausch et al.). At higher luminances, these tradeoffs are not as great unless contrast and resolution are very poor.

Luminance level is related to flicker which, as explained in the previous section, is believed to be associated with simulator sickness. To avoid flicker, refresh rate must increase as luminance level increases (Farrell et al., 1988) and, with high

refresh rates, luminance can be any level. However, faster refresh rates are associated with higher display costs. Thus, dusk conditions (i.e., lower luminance) may be simulated in systems with slower refresh rates in order to prevent flicker (Pausch et al., 1992).

Method of movement

Regan (1993) suggested that the method used to move through the virtual environment may be associated with sickness incidence. An unnatural form of movement - such as her 3D mouse - might create a cue conflict situation between inputs to the visual, vestibular, and proprioceptive systems. She suggested that the movement of a subject in a VE could be coupled to movement on a treadmill. This might provide relatively normal vestibular motion cues and lessen sickness. An upcoming ARI experiment will investigate the use of a treadmill as a device for traversing virtual terrain.

Rate of linear or rotational acceleration

McCauley and Sharkey (1992) pointed out that the flight task must be considered when assessing the adequacy of the motion provided by a motion base. Simulation of aggressive maneuvers suffers from the physical limits of the simulator to represent the acceleration cues of the maneuver. The visual display system, however, is not as limited. Although data relating the maneuvering intensity and sickness are not completely consistent and no clear conclusions can be drawn, McCauley and Sharkey suggested that increased maneuvering aggressiveness may result in increased incidence of sickness. Thus, they recommended that tasks requiring high rates of linear or rotational acceleration should be avoided or kept brief until full adaptation to the virtual environment has been achieved.

Self-movement speed

Global visual flow is a function of velocity through the virtual environment. Extremely slow speeds provide no indication of movement, whereas extremely high speeds result in blur. McCauley and Sharkey (1992) recommended that self-movement in a virtual environment should be at low speeds to reduce the effect of global visual flow on sickness. Although either extreme reduces vection, the feeling of presence in the VE may also be reduced. Thus, a breakdown in the user's acceptance of being "in" the virtual environment may occur.

Sitting vs. standing

As was noted earlier in this section, Reason and Brand (1975) stated that a significant reduction in motion sickness occurs when an individual adopts a supine position, possibly

because of the restricted motion of the head. In most experiments with virtual environments, however, subjects are likely to be either standing or sitting. Based on their theory of motion sickness, Riccio and Stoffregen (1991) would predict that less sickness would occur for seated subjects because of reduced demands on postural control.

Regan (1993) investigated this issue and compared subjects who sat while using a VE system to subjects who stood. A total of 44 subjects were exposed to a virtual environment for 10 minutes. Of the 20 seated subjects, 55% reported ratings greater than 1 during the session whereas, of the 24 standing subjects, 46% reported ratings greater than 1 (Regan's rating scale is discussed earlier in this report). Although comparison of the mean ratings of the subjects yielded non-significant results, it was noted that the higher ratings of moderate and severe nausea were reported only in the sitting group.

Type of application

McCauley and Sharkey (1992) have classified VE applications as "near" and "far". "Near" applications are those which involve proximate objects, stationary self, and the absence of vection (discussed later in this section). Because such applications do not involve whole-body rotations or linear accelerations, vestibular function is primarily limited to head movements. "Far" applications are those which involve distant objects, self-motion through the environment, and vection. It is in these applications that the vestibular input does not correspond to the visual display. Thus, McCauley and Sharkey have predicted that sickness will occur primarily in "far" applications.

Unusual maneuvers

In addition to tasks with high rates of linear or rotational acceleration, extraordinary or unusual situations should also be avoided as some have been found to be unsettling (McCauley & Sharkey, 1992). Two possibly nauseogenic maneuvers identified by McCauley and Sharkey are abruptly freezing the simulation and "flying" backwards. Frank & Casali (1986) also recommended that situational reset be avoided: the scene should not be rapidly reset forward or backward in time. They also advised that the scene be blanked for simulator entrance and exit in order to avoid possibly disorienting effects. These recommendations have direct applications for HMDs: either the visual display should be turned off or the subject should be asked to close her or his eyes when such procedures are necessary.

Vection

One phenomenon closely involved with simulator sickness is that of illusory self-motion, known as vection. Kennedy et al.

(1988) stated that visual representations of motion have been shown to affect the vestibular system. Thus, they conclude that the motion patterns represented in the visual displays of simulators may exert strong influences on the vestibular system.

Kennedy, Berbaum, et al. (1993) stated that the impression of vection produced in a simulator determines both the realism of the simulator experience and how much the simulator promotes sickness. They suggested that the most basic level of realism is determined by the strength of vection induced by a stimulus. For a stimulus which produces a strong sense of vection, correspondence between the simulated and real-world stimuli determines whether or not the stimulus leads to sickness.

Displays which produce strong vestibular effects are likely to produce the most simulator sickness (Kennedy, et al., 1988). Thus, Hettinger et al. (1990) hypothesized that vection must be experienced before sickness can occur in fixed-base simulators. While viewing each of three 15-minute motion displays, subjects rated the strength of experienced feelings of vection using a potentiometer. In addition, before the first display and after each of the three displays, the subjects completed a questionnaire which addressed symptoms of simulator sickness. Of the 15 subjects, 10 were classified as sick, based on their questionnaire score. As for vection, subjects tended to report either a great deal of vection or none at all. In relating vection to sickness, it was found that of the 5 subjects who reported no vection, only 1 became sick; of the remaining 10 subjects who had experienced vection, 8 became sick. Based on their results, Hettinger et al. concluded that visual displays that produce vection are more likely to produce simulator sickness. It is also likely that individuals who are prone to experience vection may be prone to experience sickness.

It was mentioned earlier in this report that a wider field-of-view produces more vection and, thus, is believed to increase the incidence and severity of sickness (Kennedy et al., 1989). Anderson and Braunstein (1985), however, induced vection using only a small portion of the central visual field and 30% of their subjects experienced motion sickness.

Summary: Potential Factors Associated with Simulator Sickness in Virtual Environments

This report has presented three global categories of factors—subject, simulator, and task—that may be associated with simulator sickness in virtual environments. Many factors were identified in each of these categories. The factors, as well as their known effects on simulator sickness and predicted effects on sickness in virtual environments, are summarized in Appendix Table A1.

Factors within the three categories are listed in alphabetical order. This is to give equal importance status to all of factors instead of implying that some factors are "above" or "below" others on some type of scale. Furthermore, the alphabetized list simplifies use in a reference capacity. For more detail on a particular factor, each entry refers to a sub-section in either the individual, simulator, or task sections. Superscripts refer to the abbreviated references at the end of the table. All of these references appear in complete form in the reference list for the report.

Table A1 attempts to integrate the major findings of the current literature as it relates to simulator sickness in virtual environments. It should be emphasized that this is a working table. Many factors have been identified which do not have a clear effect on sickness. Thus, this table will see many modifications and more information can be added as the state of the research progresses.

Areas for Future Research Suggested by the Literature

Correlating visual scene elements with simulator sickness

Kennedy, Berbaum, et al. (1993) reported on preliminary work being done to record the visual scene in flight simulators via video frame-by-frame decomposition. The ultimate goal of this endeavor is to analyze the visual scene and relate elements of it to the incidence of simulator sickness. In the initial study, they have attempted to identify the attributes most likely to be related to sickness. Future work will attempt to address the relationship of those attributes to simulator sickness.

Eye strain

It was discussed earlier that Stone (1993) has expressed concern over effects of the head-mounted display on the visual system. Although anecdotal evidence for such effects abounds, scientific evidence is lacking. Thus, Stone has recommended that applied psychology and ophthalmic research be combined to form an international standard. He has also recommended that a standard virtual test environment be developed which could form a foundation for an experimental paradigm, as well as provide a means of testing new VE equipment. One such test battery, the Virtual Environment Performance Assessment Battery, has been developed and tested by the Army Research Institute (Knerr, Lampton, Bliss, Moshell, & Blau, 1993).

Physiological measures of simulator sickness

The most common measures of simulator sickness are questionnaires and postural tests. Physiological measures are not often used, possibly because of equipment costs or effort

involved with their use. Additionally, the reliabilities and sensitivities of physiological measures are often low or unknown. Money (1970), in a comprehensive review of the signs and symptoms of motion sickness, found no clear results concerning physiological data.

As part of the construction of a physiological monitoring system for simulator sickness, Miller, Sharkey, Graham, and McCauley (1993) demonstrated the sensitivity of physiological measures to the severity of sickness as measured by self-reports from U.S. Army helicopter pilots. Five physiological measures were employed: tachygastria, normal myoelectrical gastric activity, skin conductance level, vagal tone, and heart period. Tachygastria and normal myoelectrical gastric activity were both reductions of energy estimates from discrete Fourier-transformed electrogastrogram (EGG) data - tachygastria were those in the 4 to 9 cycles per minute (cpm) range and normal myoelectrical gastric activity were 3 cpm. Skin conductance level was measured from electrodes placed on the flexor portion of the forearm. Vagal tone was derived from a reduction of electrocardiogram (ECG) data and provided an index of parasympathetic activity, measuring the middle component (0.12 to 0.40 Hz) of respiratory sinus arrhythmia. Another reduction of the ECG data provided the reciprocal of heart rate, heart period. Of the five physiological measures compared, heart period, tachygastria, and skin conductance level were found to be more sensitive to simulator sickness than were vagal tone and normal myoelectrical gastric activity.

Miller et al. (1993) plan to continue their research on physiological measures of simulator sickness and hope to develop them to increased sensitivity. Physiological measures, if found to be both reliable and valid, would offer objective measures of simulator sickness. Ideally, such measures would correlate with the subjective techniques typically used today. Kennedy et al. (1988) pointed out that accurate measurement of simulator sickness is not a trivial matter. A solid combination of objective and subjective measures may offer the best solution to the measurement issue.

Conclusions

The simulator sickness literature forms an excellent foundation for the study of sickness in virtual environments and many potentially important factors have been identified from the literature reviewed in this report. The tentative relationships presented should be used as a guide for future research to clarify the role of these factors in sickness. Unfortunately, due to the high cost of VE research, studies usually attempt to address as many research questions as possible and studies addressing only the issue of sickness may not be practical at this time. However, since many VE researchers recognize the

importance of studying sickness, some type of related data are usually gathered during the course of an experiment. Although these measures are usually not the primary focus of the experiment, they provide at least some basis for further study.

From the inception of its research program on virtual environments, ARI has recognized the importance of measuring aftereffects. Specifically, ARI includes both a pre- and post-immersion SSQ, or some variation of the SSQ, as part of its research. In addition to SSQ data, ARI also measures changes in postural stability to determine ataxic decrements due to exposure. These data are gathered using both traditional measures, such as the ataxia tests discussed earlier in this report, and head tracking technology, which may provide a more sensitive measure.

Sickness in virtual environments clearly warrants further investigation and the means to do so can be reasonably incorporated into any VE experiment, regardless of its primary research question. Questionnaires and postural tests - both commonly performed on military pilots as part of simulator training - can be administered simply and in a minimal amount of time. Such data collection is especially easy during the post-exposure data collection segment since, for safety purposes, subjects are commonly kept for a period of time after simulator exposure.

If the necessary research cannot be performed in a virtual environment, the next best thing would be to continue to study relevant issues in the flight/driving simulator environment and extrapolate the results to virtual environments. Although much is known about simulator sickness, many of the results are contradictory. As is the case with simulator sickness, there appears to be no one single cause of sickness in virtual environments. As a large part of this report has demonstrated, both individual factors and technical problems are likely to interact. Thus, as the search for cause and cure goes on, there remain many unanswered questions and many possible research areas.

To aid VE research, this report has presented a review of the literature covering many aspects of simulator sickness in virtual environments. Simulator sickness is a matter of concern to the new field of VE technology, partly because simulator sickness has been such a major concern in flight simulators. The significance of simulator sickness was underscored by the identification of four major consequences of it: decreased simulator use, compromised training, ground safety, and flight safety. Cue conflict was presented as the primary explanation for the occurrence of simulator sickness and is currently the primary explanation for the occurrence of sickness in virtual environments as well. Postural instability was presented as an

alternative explanation. There are many results/symptoms of simulator sickness, but the major results/symptoms pointed out in this report are those identified by the SSQ (i.e., nausea, oculomotor discomfort, and disorientation), as well as ataxia, flashbacks, eye strain, performance changes, and dark focus shifts. Along with flashbacks, ataxia is especially problematic since it can last several hours after simulator exposure and, theoretically, after exposure to a virtual environment. Additionally, flashbacks can occur suddenly, long after the simulator experience has ended - another important result possibly applicable to virtual environments. Three major quantitative tools used in the study of simulator sickness were discussed: the Simulator Sickness Questionnaire (SSQ), ataxia tests, and the Motion Sickness History Questionnaire. Areas for future research suggested by the literature as well as suggestions for future research were discussed.

The bulk of this report was devoted to identifying and discussing three categories of factors which are potentially involved with simulator sickness in virtual environments: those associated with the individual, the simulator, and the simulated task. From the literature presented, the factors within these three categories, along with their possible effects, were organized into a table. It should be emphasized that many of the relationships identified are tentative. Nevertheless, this report can serve as a guide for future research to clarify the role of these factors and, possibly, to identify additional factors involved in simulator sickness in virtual environments.

REFERENCES

Arditi, A. (1986). Binocular vision. In K. Boff, L. Kaufman, & J. Thomas (Eds.), Handbook of Perception & Human Performance, (Chapter 23). New York: John Wiley & Sons.

Anderson, G. J., & Braunstein, M. L. (1985). Induced self-motion in central vision. Journal of Experimental Psychology: Human Perception and Performance, 11(2), 122-132.

Antonoff, M. (1993, June). Living in a virtual world. Popular Science, 83-86, 124, 125.

Baltzley, D. R., Kennedy, R. S., Berbaum, K. S., Lilienthal, M. G., & Gower, D. W. (1989). The time course of postflight simulator sickness symptoms. Aviation, Space, and Environmental Medicine, 60(11), 1043-1048.

Barrett, G. V., & Thornton, C. L. (1968). Relationship between perceptual style and simulator sickness. Journal of Applied Psychology, 52(4), 304-308.

Barrett, G. V., Thornton, C. L., & Cabe, P. A. (1969). Relationship between embedded figures test performance and simulator behavior. Journal of Applied Psychology, 53(3), 253-254.

Barrett, G. V., Thornton, C. L., & Cabe, P. A. (1970). Cue conflict related to perceptual style. Journal of Applied Psychology, 54(3), 258-264.

Biocca, F. (1992). Will simulation sickness slow down the diffusion of virtual environment technology? Presence, 1(3), 334-343.

Boff, K. R., & Lincoln, J. E. (1988). Engineering data compendium: Human perception & performance. AAMRL, Wright-Patterson AFB, OH, 166-91.

Botwinick, J., & Brinley, J. F. (1963). Age differences in relations between CFF and apparent motion. Journal of Genetic Psychology, 102, 189-194.

Casali, J. G. (1986). Vehicular simulation-induced sickness, Volume 1: An overview. IEOR Technical Report No. 8501. (NTSC TR 86-010). Orlando, FL: Naval Training Systems Center.

Casali, J. G., & Wierwille, W. W. (1986). Vehicular simulation-induced sickness, Volume III: Survey of etiological factors and research facility requirements. IEOR Technical Report No. 8503. (NTSC TR 86-012). Orlando, FL: Naval Training Systems Center.

Crowley, J. S. (1987). Simulator sickness: A problem for Army aviation. Aviation, Space, and Environmental Medicine, 58(4), 355-357.

Dichgans, J., & Brandt, T. (1973). Optokinetic motion sickness and pseudo-coriolis effects induced by moving visual stimuli. Acta Otolaryngologica, 76, 339-348.

Duke-Elder, S., & Abrams, D. (1970). Eye-strain. In S. Duke-Elder (Ed.), System of ophthalmology (Vol. V, Chap. XV). St. Louis: C. V. Mosby.

Ebenholtz, S. M. (1977). Determinants of the rod and frame effect: The role of retinal size. Perception & Psychophysics, 22(6), 531-538.

Ebenholtz, S. M. (1992). Motion sickness and oculomotor systems in virtual environments. Presence, 1(3), 302-305.

Ehrlich, J., Singer, M. J., & Cinq-Mars, S. (In preparation). Stereoscopic and Monoscopic Displays in Virtual Environments (ARI Technical Report). Alexandria, VA: U.S. Army Research Institute for the Behavioral and Social Sciences.

Farrell, J. E., Casson, E. J., Haynie, C. R., & Benson, B. L. (1988, July). Designing flicker-free video display terminals. Displays, 9(7), 115-122.

Fowlkes, J. E., Kennedy, R. S., Hettinger, L. J., & Harm, D. L. (1993). Changes in the dark focus of accommodation associated with simulator sickness. Aviation, Space, and Environmental Medicine, 64(7), 612-618.

Fowlkes, J. E., Kennedy, R. S., & Lilienthal, M. G. (1987). Postural disequilibrium following training flights. Proceedings of the 31st Annual Meeting of the Human Factors Society, 488-491.

Frank, L. H., & Casali, J. G. (1986). Simulator sickness: A review of its costs, countermeasures, and prediction (Technical Paper 861782). Warrendale, PA: Society of Automotive Engineers.

Frank, L. H., Casali, J. G., & Wierwille, W. W. (1988). Effects of visual display and motion system delays on operator performance and uneasiness in a driving simulator. Human Factors, 30(2), 201-217.

Goldstein, E. B. (1989). Sensation and perception (3rd ed.). Belmont, CA: Wadsworth Publishing Company.

Grandjean, E. (1988). Fitting the task to the man. London: Taylor & Francis.

Guedry, F. E., & Montague, E. K. (1961). Quantitative evaluation of the vestibular Coriolis reaction. Aviation, Space, and Environmental Medicine, 32(6), 487-500.

Hamilton, K. M., Kantor, L., & Magee, L. E. (1989). Limitations of postural equilibrium tests for examining simulator sickness. Aviation, Space, and Environmental Medicine, 60(3), 246-251.

Harwood, K., & Foley, P. (1987). Temporal resolution: An insight into the video display terminal (VDT) "Problem." Human Factors, 29(4), 447-452.

Hettinger, L. J., Berbaum, K. S., Kennedy, R. S., Dunlap, W. P., & Nolan, M. D. (1990). Vection and simulator sickness. Military Psychology, 2(3), 171-181.

Jones, S. A. (1993, April). Simulator sickness implications for advanced training technologies. Proceedings of the 7th International Symposium on Aviation Psychology.

Jones, S. A.,, Kennedy, R. S., Lilienthal, M. G., & Berbaum, K. S. (Unpublished manuscript). Comparison of simulator sickness incidence in two Navy flight trainers: A field investigation. Orlando, FL: Essex Corporation.

Kellogg, R. S., & Gillingham, K. K. (1986). United States Air Force experience with simulator sickness, research and training. Proceedings of the 30th Annual Meeting of the Human Factors Society, 1, 427-429.

Kellogg, R. S., Kennedy, R. S., & Graybiel, A. (1965). Motion sickness symptomatology of labyrinthine defective and normal subjects during zero gravity maneuvers. Aerospace Medicine, 4, 315-318.

Kennedy, R. S., Allgood, G. O., Van Hoy, B. W., & Lilienthal, M. G. (1987). Motion sickness symptoms and postural changes following flights in motion-based flight trainers. Journal of Low Frequency Noise and Vibration, 6(4), 147-154.

Kennedy, R. S., Berbaum, K. S., Lilienthal, M. G., Dunlap, W. P., Mulligan, B. F., & Funaro, J. F. (1987, March). Guidelines for alleviation of simulator sickness symptomatology. (NAVTRASYSCEN TR-87007) (AD-A182 554 NAVTRASYSCEN TR-87007). Orlando, FL: Naval Training Systems Center.

Kennedy, R. S., Berbaum, K. S., & Smith, M. G. (1993). Methods for correlating visual scene elements with simulator sickness incidence. Proceedings of the 37th Annual Meeting of the Human Factors and Ergonomics Society, 2, 1252-1256.

Kennedy, R. S., & Fowlkes, J. E. (1992). Simulator sickness is polygenic and polysymptomatic: Implications for research. International Journal of Aviation Psychology, 2(1), 23-38.

Kennedy, R. S., Fowlkes, J. E., Berbaum, K. S., & Lilienthal, M. G. (1992). Use of a motion sickness history questionnaire for prediction of simulator sickness. Aviation, Space, and Environmental Medicine, 63(7), 588-593.

Kennedy, R. S., Fowlkes, J. E., & Lilienthal, M. G. (1993). Postural and performance changes following exposures to flight simulators. Aviation, Space, and Environmental Medicine, 64(10), 912-920.

Kennedy, R. S., & Frank, L. H. (1983). A review of motion sickness with special reference to simulator sickness. Paper presented at the National Academy of Sciences/National Research Council Committee on Human Factors, Workshop on Simulator Sickness, 26-28 September 1983, Naval Postgraduate School, Monterey, CA.

Kennedy, R. S., Hettinger, L. J., & Lilienthal, M. G. (1988). Simulator sickness. In G. H. Crampton (Ed.), Motion and Space Sickness, Chapter 15, 317-341. Boca Raton, FL: CRC Press.

Kennedy, R. S., Lane, N. E., Berbaum, K. S., & Lilienthal, M. G. (1993). A simulator sickness questionnaire (SSQ): A new method for quantifying simulator sickness. International Journal of Aviation Psychology, 3(3), 203-220.

Kennedy, R. S., Lilienthal, M. G., Berbaum, K. S., Baltzley, D. R., & McCauley, M. E. (1989). Simulator sickness in U.S. Navy flight simulators. Aviation, Space, and Environmental Medicine, 60(1), 10-16.

Knerr, B. W., Lampton, D. R., Bliss, J. P., Moshell, J. M., & Blau, B. S. (1993, July). Human performance in virtual environments: Initial experiments. Proceedings of the 29th International Applied Military Psychology Symposium. Wolfson College, Cambridge, UK.

Kolasinski, E. M., Jones, S. A., Kennedy, R. S., & Gilson, R. D. (1994, October). Postural stability and its relation to simulator sickness. Poster session presented at the 38th Annual Meeting of the Human Factors and Ergonomics Society. Abstract appears in Proceedings of the 38th Annual Meeting of the Human Factors and Ergonomics Society, vol. 2, 980.

Levine, M. W., & Shefner, J. M. (1991). Fundamentals of sensation and perception. Belmont, CA: Wadsworth, Inc.

Levison, W. H., & Pew, R. W. (1993, February). Use of Virtual Environment Training Technology for Individual Combat Simulation (ARI Technical Report 971). Alexandria, VA: U.S. Army Research Institute for the Behavioral and Social Sciences. (AD A263 546)

Long, G. M., Ambler, R. K., & Guedry, F. E. (1975). Relationship between perceptual style and reactivity to motion. Journal of Applied Psychology, 60(5), 599-605.

Maxwell, C. A. (1992, November). Flicker science and the consumer. Information Display, 7-10.

McCauley, M. E., & Sharkey, T. J. (1992). Cybersickness: Perception of self-motion in virtual environments. Presence, 1(3), 311-318.

Miller, J. C., Sharkey, T. J., Graham, G. A., & McCauley, M. E. (1993). Autonomic physiological data associated with simulator discomfort. Aviation, Space, and Environmental Medicine, 64(9), 813-819.

Money, K. E. (1970). Motion sickness. Physiological Reviews, 50(1), 1-39.

Owen, D. H. (1990). Perception and control of changes in self-motion: A functional approach to the study of information and skill. In R. Warren & A. H. Wertheim (Eds.), Perception and control of self-motion. Hillsdale, NJ: Lawrence Erlbaum.

Parker, D. E., & Harm, D. L. (1992). Mental rotation: A key to mitigation of motion sickness in the virtual environment? Presence, 1(3), 329-333.

Pausch, R., Crea, T., & Conway, M. (1992). A literature survey for virtual environments: Military flight simulator visual systems and simulator sickness. Presence, 1(3), 344-363.

Reason, J. T., & Brand, J. J. (1975). Motion sickness. London: Academic Press.

Regan, E. C. (1993). Side-effects of immersion virtual reality. Paper presented at the International Applied Military Psychology Symposium, July 26-29.

Regan, E. C., & Price, K. R. (1993). Some side-effects of immersion virtual reality: An investigation into the relationship between inter-pupillary distance and ocular related problems. Army Personnel Research Establishment Report 93R023.

Rheingold, H. (1991). Virtual reality. New York: Simon & Schuster.

Riccio, G. E., Martin, E. J., & Stoffregen, T. A. (1992). The role of balance dynamics in the active perception of orientation. Journal of Experimental Psychology: Human Perception and Performance, 18(3), 624-644.

Riccio, G. E., & Stoffregen, T. A. (1991). An ecological theory of motion sickness and postural instability. Ecological Psychology, 3(3), 195-240.

Rinalducci, E. J., & MacArthur, M. (Unpublished manuscript). Annotated bibliography on the effects of flicker on simulator sickness. Institute for Simulation and Training, University of Central Florida, Division of Sponsored Research, Orlando, FL.

Sharkey, T. J., & McCauley, M. E. (1992). Does a motion base prevent simulator sickness? Proceedings of the AIAA/AHS Flight Simulation Technologies Conference (pp. 21-28) (Report Number AIAA-92-4133-CP). Washington, DC: AIAA.

Stern, R. M., Hu, S., LeBlanc, R., & Koch, K. L. (1993). Chinese hyper-susceptibility to vection-induced motion sickness. Aviation, Space, and Environmental Medicine, (9), 827-830.

Stoffregen, T. A., & Riccio, G. E. (1988). An ecological theory of orientation and the vestibular system. Psychological Review, 95(1), 3-14.

Stoffregen, T. A., & Riccio, G. E. (1991). An ecological critique of the sensory conflict theory of motion sickness. Ecological Psychology, 3(3), 15-194.

Stone, B. (1993, October/November). Concerns raised about eye strain in VR systems. Real Time Graphics, 2(4), 1-3, 6, 13.

Thomley, K. E., Kennedy, R. S., & Bittner, A. C. (1986). Development of postural equilibrium tests for examining environmental effects. Perceptual and Motor Skills, 63, 555-564.

Thorell, L. G., & Smith, W. J. (1990). Using computer color effectively. Englewood Cliffs, NY: Englewood Cliffs.

Treisman, M. (1977). Motion sickness: An evolutionary hypothesis. Science, 197, 493-495.

Tyler, D. B., & Bard, P. (1949). Motion sickness. Physiological Review, 29(10), 311-369.

Uliano, K. C., Lambert, E. Y., Kennedy, R. S., & Sheppard, D. J. (1986). The effects of asynchronous visual delays on simulator flight performance and the development of simulator sickness symptomatology (NAVTRASYSCEN 85-D-0026-1). Orlando, FL: Naval Training Systems Center.

Welch, R. B. (1978). Perceptual modification: Adapting to altered sensory environments. New York: Academic Press.

Welch, R. B. (1986). Adaptation of space perception. In K. Boff, L. Kaufman, & J. Thomas (Eds.), Handbook of perception and human performance, (Vol. 1, Chap. 24). New York: John Wiley.

Wilson, T. R. (1963). Flicker fusion frequency, age, and intelligence. Gerontologia, 7, 200-208.

Witkin, H. A., Moore, C. A., Goodenough, D. R., & Cox, P. W. (1977). Field-dependent and field-independent cognitive styles and their educational implications. Review of Educational Research, 47(1), 1-64.

Appendix

Potential Factors Associated with Simulator Sickness in Virtual Environments

INDIVIDUAL		
FACTOR	**EFFECT(S)**	**COMMENTS**
age	motion sickness susceptibility greatest between the ages of 2 and 12; after 12, susceptibility decreases until almost nonexistent after age 50[1]	related to experience with the real-world task
concentration level	higher levels of concentration may be associated with lower levels of sickness[2]	further research needed
ethnicity	Asian individuals may be more susceptible to visually-induced motion sickness[3]	possibly due to environmental factors or genetic differences in central catecholamine release[3]
experience with real-world task	experienced pilots have greater incidence of sickness than do novices[4]	results not fully consistent in the literature
experience with simulator (adaptation)	increased simulator experience usually results in decreased sickness[5]	may cause problems upon return to the normal environment[6]
flicker fusion frequency threshold	• decreases at night[7] • substantial individual variability[8,9,10]	definition: the point at which flicker becomes perceptible

(table continues)

INDIVIDUAL		
FACTOR	**EFFECT(S)**	**COMMENTS**
gender	females may be more susceptible to motion sickness[11]	females exhibit larger FOVs[6]
illness and personal characteristics	many forms of illness may result in increased susceptibility to simulator sickness[4,11]	possible effect of characteristics such as motivation, goals, or belief of susceptibility?
mental rotation ability	greater ability may be related to a decrease in space motion sickness[12]	mental rotation must occur for an individual to recognize objects which are not in their usual orientations[12]
perceptual style	• field-independent individuals have been predicted to have higher sickness rates[13] • field-dependent individuals have demonstrated higher sickness rates in several studies[14,15]	results are inconclusive
postural stability	• an alternative to the cue conflict theory proposes that postural instability causes motion and simulator sickness[16] • good pre-simulator postural stability may be associated with less sickness[17]	possible implications for liability issues concerned with public-use VR systems

(table continues)

SIMULATOR		
FACTOR	**EFFECT(S)**	**COMMENTS**
binocular viewing	stereoscopic displays may result in increased sickness[18]	definitions: • monoscopic display: same image presented to both eyes • stereoscopic display: slightly different images presented to each eye
calibration	poor calibration may lead to various distortions which could lead to sickness due to distorted graphics[19]	commercial VR systems might suffer from lack of regularly scheduled calibration[19]
color	color displays may have lower resolution[20]	color is detected by the foveal visual system but motion is largely detected by the peripheral system[21]
contrast	with poor contrast there are more tradeoffs among required contrast, luminance, and resolution; luminance level is related to flicker[20]	definition: the ratio of the highest luminance in the display to the lowest[20]
field of view (FOV)	wider FOV increases both: • incidence and severity of sickness[22] • likelihood of perception of flicker[9]	to avoid flicker, refresh rate must increase as FOV increases[9]

(table continues)

SIMULATOR		
FACTOR	**EFFECT(S)**	**COMMENTS**
flicker	flicker is distracting, induces eye fatigue, and appears to be associated with sickness[23,20,24]	• to avoid flicker, refresh rate must increase as both luminance and FOV increase[25,9] • perception of flicker depends on an individual's flicker fusion frequency threshold
inter-pupillary distance	fixed distance in head mounted displays may contribute to ocular discomfort[26]	individual variations may require adjustable system parameters
motion platform	• non-correspondence of visual and motion cues may cause sickness[27] • motion may produce motion sickness[28] • moving-base simulators may increase ataxia[29]	• simple random vibration is not enough to reduce sickness[27] • most likely not an engineering solution to sickness[30]
phosphor lag	if excessive, causes smearing which may lead to sickness due to distorted images[20]	definition: the continued glowing of the CRT phosphor from one frame to the next[20]
position-tracking error	may lead to cue conflicts[11]	the position tracker in a VR system provides information about the location of the user's head and limbs in space

(table continues)

SIMULATOR		
FACTOR	**EFFECT(S)**	**COMMENTS**
refresh rate	slower refresh rates promote flicker and may lead to phosphor lag; refresh rate, FOV, and luminance level interact in their effect on flicker[20]	• definition: the frequency with which the CRT's electron beam relights the phosphor pixels[31] • to avoid flicker, refresh rate must increase as both luminance and FOV increase[25,9]
resolution	with poor resolution there are more tradeoffs among required contrast, luminance, and resolution; luminance level is related to flicker[20]	resolution is a measure of the level of detail provided by the display[20]
scene content	affects update rate[20]	definition: the level of detail available for a given scene[20]
time lag (transport delay)	increased lag may lead to increased sickness[20]	can occur between information input and motion or visual output[20]
update rate (frame rate)	slow update rate could lead to visual lag	• definition: the rate at which subsequent frames of the scene can be generated and rendered into the frame buffer for display[20] • affected by scene complexity and available computing power[20]

(table continues)

SIMULATOR		
FACTOR	**EFFECT(S)**	**COMMENTS**
viewing region	image distortion increases as distance from design eyepoint increases[20]	the optimal viewing position within the viewing region is called the design eyepoint[20]

(table continues)

TASK		
FACTOR	**EFFECT(S)**	**COMMENTS**
altitude above terrain	to decrease sickness in flying tasks, decrease global visual flow by using higher altitude[19]	one of the strongest contributors to sickness[32]
degree of control	sickness rates usually lower for persons with higher degree of control[20]	controlling allows for anticipation of future motion so that cue conflict can be reduced or eliminated
duration	as duration increases: • intensity and duration of ataxia increases[33] • sickness incidence may increase[19] • adaptation time may increase[19]	effect of motion base on ataxia increases as task duration increases[29]
global visual flow	to minimize sickness, self-movement should be at high altitudes and/or at low speeds[19]	definition: maximum global visual flow = velocity / eye height above surface[34]
head movements	rapid and intense head movements may be associated with increased sickness; results inconclusive thus far[2]	known to be associated with sickness because of Coriolis and pseudo-Coriolis stimulation[35,36]

(table continues)

TASK		
FACTOR	**EFFECT(S)**	**COMMENTS**
luminance level	at low luminances, there are more tradeoffs with required contrast, luminance, and resolution; luminance level is related to flicker[20]	• definition: the intensity or brightness of the light coming from the display[20] • to avoid flicker, refresh rate must increase as luminance level increases[25] • dusk conditions may be simulated in systems with slower refresh rates[20]
method of movement	may contribute to cue conflict[2]	upcoming ARI experiment will couple movement on treadmill to movement in VE
rate of linear or rotational acceleration	high rates may increase sickness[19]	reduce or limit aggressive movements until full adaptation to VE has occurred[19]
self-movement speed	to decrease effect of global visual flow on sickness, self-movement should be at low speeds[19]	the relationship between speed and self-motion perception is an inverted "U"
sitting vs. standing	sitting should be less conducive to sickness[16]	results thus far inconclusive[2]

(table continues)

TASK		
FACTOR	**EFFECT(S)**	**COMMENTS**
type of application	"far" applications may be more sickness-inducing than "near" applications[19]	definitions[19]: • "far" applications involve distant objects, self-motion through the environment, and vection • "near" applications involve proximate objects, stationary self, and no vection
unusual maneuvers	may be unsettling[19]	turn off HMD or ask viewer to close eyes if unusual maneuvers are necessary
vection	• believed to be a precursor to sickness[37] • increases as FOV increases[22] • can also be produced by stimuli having 3D cues, presented to a small, central FOV[38]	• definition: visually induced perception of self-motion • visual representations of motion can affect the vestibular system[39]

(table continues)

Table Notes

[1]Reason & Brand (1975)
[2]Regan (1993)
[3]Stern, Hu, LeBlanc, & Koch (1993)
[4]Kennedy, Berbaum, Lilienthal, Dunlap, Mulligan, & Funaro (1987)
[5]Uliano, Lambert, Kennedy, & Sheppard (1986)
[6]Kennedy & Frank (1983)
[7]Grandjean (1988)
[8]Botwinick & Brinley (1963)
[9]Maxwell (1992)
[10]Wilson (1963)
[11]Biocca (1992)
[12]Parker & Harm (1992)
[13]Barrett & Thornton (1968)
[14]Barrett, Thornton, & Cabe (1970)
[15]Long, Ambler, & Guedry (1975)
[16]Riccio & Stoffregen (1991)
[17]Kolasinski, Jones, Kennedy, & Gilson (1994)
[18]Ehrlich, Singer, & Cinq-Mars (in preparation)
[19]McCauley & Sharkey (1992)
[20]Pausch, Crea & Conway (1992)
[21]Levine & Shefner (1991)
[22]Kennedy, Lilienthal, Berbaum, Baltzley, & McCauley (1989)
[23]Harwood & Foley (1987)
[24]Rinalducci & MacArthur (1990)
[25]Farrell, Casson, Haynie, & Benson (1988)
[26]Regan & Price (1993)
[27]Casali (1986)
[28]Kennedy, Allgood, Van Hoy, & Lilienthal (1987)
[29]Kennedy, Fowlkes, & Lilienthal (1993)
[30]Sharkey & McCauley (1992)
[31]Thorell & Smith (1990)
[32]Kennedy, Berbaum, & Smith (1993)
[33]Fowlkes, Kennedy, & Lilienthal (1987)
[34]Owen (1990)
[35]Dichgans & Brandt (1973)
[36]Guedry & Montague (1961)
[37]Hettinger, Berbaum, Kennedy, Dunlap, & Nolan (1990)
[38]Anderson & Braunstein (1985)
[39]Kennedy, Hettinger, & Lilienthal (1988)