A Literature Survey for Virtual Environments: Military Flight Simulator Visual Systems and Simulator Sickness

Abstract

Researchers in the field of virtual environments (VE), or virtual reality, surround a participant with synthetic stimuli. The flight simulator community, primarily in the U.S. military, has a great deal of experience with aircraft simulations, and VE researchers should be aware of the major results in this field. In this survey of the literature, we have especially focused on military literature that may be hard for traditional academics to locate via the standard journals. One of the authors of this paper is a military helicopter pilot himself, which was quite useful in obtaining access to many of our references. We concentrate on research that produces specific, measured results that apply to VE research. We assume no background other than basic knowledge of computer graphics, and explain simulator terms and concepts as necessary. This paper ends with an annotated bibliography of some harder to find research results in the field of flight simulators:

- The effects of display parameters, including field-of-view and scene complexity;
- The effect of lag in system response;
- The effect of refresh rate in graphics update;
- The existing theories on causes of simulator sickness; and
- The after-effects of simulator use

Many of the results we cite are contradictory. Our global observation is that with flight simulator research, like most human–computer interaction research, there are very few "correct" answers. Almost always, the answer to a specific question depends on the task the user was attempting to perform with the simulator.

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1 Introduction

Researchers in the field of virtual environments surround a participant with synthetic stimuli. Therefore, VE researchers must be aware of the phenomena that can occur when various aspects of the stimuli cause undesired artifacts. The flight simulator community, primarily in the U.S. military, has a great deal of experience with aircraft simulations, and VE researchers should be aware of the major results in this field.

In flight simulation, the basic goal is to develop aviation skills that the pilot can then transfer to a real-world mission. In this paper, we present major results from the flight simulation literature about both the measured success of skill transfer, and the effects of simulator sickness and simulator after-effects. Many of the results we found were contradictory; the specific task being performed must be taken into account when asking even the most basic questions regarding the efficacy of simulator technology.

2 Transference of Skill

That a pilot can train in a simulator to gain experience about a real aircraft is taken as given today, but this was not always so. Initially, many aviators were skeptical about the training value of simulators and preferred training in the actual aircraft. As the government trimmed operational budgets, the military needed to

Randy Pausch, Thomas Crea, and Matthew Conway
Department of Computer Science
University of Virginia, School of Engineering
Charlottesville, Virginia 22903-2442

reduce flight training costs and directed research efforts toward cost-effectiveness studies. Orlansky and String (1977) investigated the studies made since 1939 and concluded that simulators had significant positive effects on training. In one study using the 2-B-24 Flight Trainer for instrument training of undergraduate helicopter pilots in the Army, Caro (1973) stated there was a "90% reduction in the amount of aircraft time to attain course objectives." Specifically, Caro (1972) showed that previous students needed 60 hr of actual aircraft time and 26 hr in the older 1-CA-1 trainer. After using the 2-B-24, students achieved the same training goals in only 6.5 aircraft hours and just under 43 simulator hours on average. Orlansky and String's results were instrumental in promoting simulator use. They concluded that "hourly operating costs of flight simulators were approximately 5% to 20% of the hourly operating costs of the aircraft they emulate." They also predicted that military flying hours would be reduced to almost 17% by 1981, and that the procurement cost of these simulators could be amortized in 2.2 years. Consequently, the military strongly encouraged flight simulator use in all areas of training. Today, simulators serve as a major training resource for the United States military services and many commercial aviation companies.

For additional transfer of training information, the reader should look at Waag's (1981) review of the literature concerning the training effectiveness of visual motion, or a collection of nearly 150 extracts compiled by Ayres, Hays, Singer, and Heinicke (1984).

3 Simulator Sickness

For all their advantages, simulators are not without their problems; many pilots experience so-called *simulator sickness.* There is a subtle difference between simulator sickness and *motion sickness.* Kennedy and Frank (1985) describe motion sickness as a general term for a collection of symptoms one experiences when subjected to abrupt, periodic, or unnatural accelerations, and common symptoms include loss of skin color, inability to coordinate voluntary muscular movements, and nausea. The term simulator sickness is typically used to refer to sickness caused by the incorrect aspects of the simulation, not sickness caused by a correct simulation of a nauseating experience, such as a turbulent airplane flight.

An examination of motion sickness is helpful here to underscore the distinction between simulator sickness and motion sickness. Motion sickness can be caused by any number of things; Casali (1985) for example, concluded from earlier research conducted by Money, that it is "generally accepted that stimulation of the vestibular apparatus of the inner ear is necessary for the inducement of motion sickness in humans." Daunton, Fox, and Crampton (1984), however, disagreed and showed that the symptoms of motion sickness, along with the illusions of self-motion, could be elicited in human subjects by visual stimulation alone. This so-called ***visually induced motion sickness*** (VIMS) happens when the user becomes sick without any vestibular (inner ear) stimulation, and, although the symptoms are similar to those of motion sickness, VIMS is really an example of simulator sickness, because it does not involve physical motion to stimulate the vestibular system.

Kennedy, Frank, and McCauley (1985) depict this subtlety in a diagram (Fig. 1) showing a schematic relationship among simulator sickness, motion sickness, and perceptual adaptation. Perceptual adaptation is the ability of the human central nervous system to adjust and respond to a stimulus more effectively the next time the stimulus is encountered. Figure 1 illustrates that although there exists overlap among each of the three, each also has its own unique characteristics. Later, Cheung, Howard, and Money (1991) identified another issue asserting, "Labyrinthine-defective subjects [those with inner-ear damage] experience no sickness symptoms, which strongly suggests that the vestibular system is necessary for sickness induced by moving visual fields."

The origins of simulator sickness are unclear and no single factor appears to cause illness in all simulators. Sickness may arise as a result of unique, individual factors or because of improper simulation from the hardware device. Some, but not all, symptoms of simulator sickness are identical to those of motion sickness.

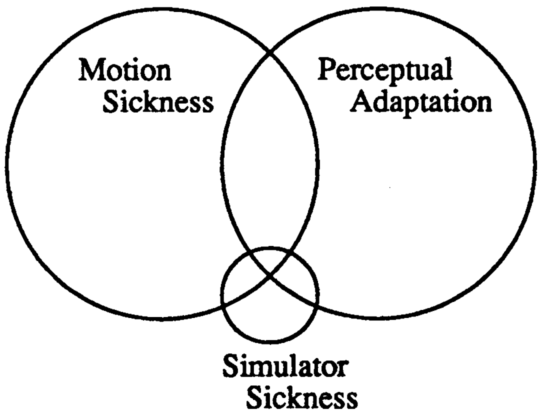

Figure 1. *The relationship between simulator sickness and motion sickness. Reproduced from Kennedy, Frank and McCauley (1985).*

Kennedy and Frank (1985) describe simulator sickness as both *polysymptomatic* (inducing many symptoms) and *polygenic* (originating from many distinct sources).

The polygenic nature of simulator sickness is readily seen: it can be caused by both moving and motionless platforms, by oscillatory motion of about 0.2 Hz (cycles/second) (Kennedy et al., 1985) and by visual imagery alone. The visual systems of simulators are vital in our understanding of the origins of simulator sickness.

4 Visual Systems

Many of the characteristics of a simulator's visual display system can be described on two levels: a quantitative, physical level and a qualitative, psychophysical (or perceptual) level. A 1981 Advisory Group for Aerospace Research and Development (AGARD) paper, "Characteristics of Flight Simulator Visual Systems," described the display system in detail and discussed visual systems in terms of energy, spatial, and temporal properties.

5 Energy Properties of Simulator Visual Systems

Several energy properties pertaining to flight simulator visual systems include:

- *Luminance*—the intensity, or brightness of the light coming from the display measured in candela per square meter.
- *Contrast*—the ratio of the highest luminescence provided by the display to the lowest.
- *Resolution*—a measurement of the level of detail provided by a display, measured in pixels per inch. This should not be confused with visual acuity, which is the ability of the human eye to recognize fine detail. For instance, the more dots/inch an individual can distinguish, the better his or her visual acuity.

Luminance, contrast, and resolution are interrelated; any adjustment of one of these variables may require and adjustment of the other two to achieve a proper visual display. Consequently, these properties must be carefully balanced with the task to be performed and the capabilities of the human visual system in order to achieve optimum performance (AGARD, 1981).

Color is another energy property whose value concerning user performance is uncertain. "Whether color should be used in visual systems is a debatable question. There is little experimental evidence of its effect, and presently no substantial objective evidence either for or against the use of color in visual flight simulators" (AGARD, 1981). In a study of bombing performance in the 2B35 TA-4J flight simulator, Kellogg, Kennedy, and Woodruff (1984) determined there were no statistically significant differences between performance with color and black-and-white visual displays. They concluded that color visual scene presentation did not enhance performance and that the only advantage was that pilots preferred the color display for aesthetic reasons. Despite the fact that "the highest resolution color television display has significantly lower resolution than many monochrome displays," there is a subjective preference of color over monochrome (AGARD, 1981). On the other hand, if tasks depend on rapid discrimination of objects, color may provide benefit: "An object is more easily recognized in color than monochrome . . . in a projected image of the sky and ground, if the sky is blue and the ground is brown/green, the pilot will rarely mistake his orientation, even in violent combat maneuvers" (AGARD, 1981).

5 Spatial Properties of Simulator Visual Systems

Several spatial properties pertain to flight-simulator visual systems, including field-of-view, the viewing region, depth perception, and scene content. We will consider each of these separately.

5.1 Field-of-View

Field-of-view is a spatial property that defines the horizontal and vertical angular dimensions of the display. Research tends to show that wider field-of-view displays enhance performance while also increasing the likelihood of simulator sickness. The exact results tend to depend on the task being performed.

Research conducted at the Naval Training Systems Center's (NTSC) Visual Technology Research Simulator (VTRS) studied field-of-view and considered its effect on performance, its cost-effectiveness, and its role in causing simulator sickness. In two carrier landing studies, Westra, Lintern, Sheppard, Thomley, Mauk, Wightman, and Chambers (1986) showed there was no transfer advantage for those trained with a wide field-of-view compared to those trained with the lower cost narrow field-of-view. In contrast, earlier studies by Westra (1983) showed that there were some advantages for the wide field-of-view conditions, although these effects were small and/or short lived and generally disappeared after the user completed a few trials within the simulator. In two other studies pertaining to helicopter shipboard landings, the advantages of a wide field-of-view were confirmed when Westra, Sheppard, Jones, and Hettinger (1987) determined pilot performance was significantly better in all phases of the approach, hover, landing, and precision hover task with the wider field-of-view display; Westra and Lintern (1985) also determined field-of-view had a marginal positive effect on a few performance measures.

The advantages gained from wider displays varied with each study and depend on the task performed. Determining the correct field-of-view for any particular simulator is not straightforward. The studies of Westra and his colleagues considered transfer of training advantages and the cost-effectiveness of a wide field-of-view, and they based their recommendations on these considerations.

In terms of increased simulator sickness, Van Cott (1990) showed that a wide field-of-view provides more stimulation and results in a more compelling display of motion. Furthermore, Kennedy, Fowlkes, and Hettinger (1989) stated that restricting the field-of-view may reduce the properties that cause nausea. These results imply that simulator sickness generally occurs more frequently and more intensely with a wider field-of-view display. While a display's field-of-view is a factor in determining whether people will experience illness, it should be understood that it is not the only factor, and therefore, must be considered in conjunction with other characteristics of the display and the task at hand.

For example, in the mid-1980s, Anderson and Braunstein (1985) studied the phenomenon of *linear vection,* the perception of self-motion induced by visual stimulation. A common example of this effect occurs when movie producers show aircraft moving at very fast rates of speed, using dots or stars to simulate spaceflight. Anderson and Braunstein were able to induce linear vection in subjects with a visual angle as small as 7.5° in the central visual field. They achieved these results by placing observers in an environment in which they were exposed to a moving display of randomly positioned dots. The researchers concluded that motion and texture in the display may be more critical than the display's field-of-view measurements.

5.2 Viewing Region

The *viewing region* is 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 point in the center of this volume is called the *design eyepoint* and represents the optimal position for the observer. As the observer moves away from the design eyepoint, the image becomes increasingly distorted; when the viewer is completely outside the volume of the viewing region, the displayed graphics disappear or their quality becomes unacceptable (AGARD, 1981).

The viewing region of most *computer-generated imagery* (often abbreviated "CGI" in the literature) is rather different from most other projective media. In a cinema, for example, the viewing region is substantially larger than that of a computer-generated simulator image. Images from film projectors degrade gradually and the imagery can be useful at locations considerably distant from the design eyepoint (AGARD, 1981). On the other hand, the fidelity of computer-generated imagery degrades quickly with distance from the design eyepoint. The smaller viewing region of CGI implies that it is possible for some simulator participants to be away from the design eyepoint, but still inside the viewing region. It is possible from this vantage point to succumb to simulator sickness induced by motion in the display and distorted visuals. Lilienthal (unpublished) stated that "In the 2F87(F) (P-3C) simulator, the flight engineer, who was behind the pilot's [location] and thus out of the design eye point of the visual system, saw distorted visual cues." He explains that flight engineers reported a significant amount of simulator sickness until they used a baffle to prevent them from having a direct view of the visual scene, and this modification reduced reports of sickness significantly. He also mentions that viewing the visual scene outside the design eyepoint causes users to see distorted visual cues that induce symptoms of simulator sickness and a lack of balance while standing.

Several of these distorted visual cues are dynamic. "Graphic displays, such as those used in flight simulator visual systems, provide accurate representations of three-dimensional space only when viewed from the geometric center of projection. If the head is moved outside the center of projection, geometric distortions occur in the projected imagery that provide inappropriate visual information for self-motion" (Rosanski, cited in Kennedy, Fowlkes, and Hettinger, 1987). Kennedy, Fowlkes, and Hettinger also state that these optical distortions may be magnified by highly detailed imagery and wide field-of-view systems, and the irregularities introduced by distortions may provide inappropriate self-motion information.

5.3 Depth Perception

Depth perception is the property of vision that allows us to see the world as three-dimensional rather than flat. Unfortunately, depth cues are difficult to simulate and it is difficult to build hardware that permits the use of *binocular vision*. Visual systems that are *biocular* (both eyes) may only provide *monocular* cues if the same image is sent to both eyes. Although humans can adapt and use monocular cues to accomplish a variety of tasks, Hale (1987) claims binocular vision is clearly superior. Hale concludes this via a literature review that included an article by Upton and Strothers that stated stereo viewing was superior to monocular viewing. In Hale's review, another paper by Martin and Warner compared four different field-of-view angles: 40° monocular, 40° binocular, 90° binocular, and 120° binocular. The subjective response from the questionnaire indicated a progressive increase in pilot ratings from the 40° monocular field-of-view to the 90° binocular field-of-view for various aspects of the mission. There was very little difference in ratings between the 90° binocular and 120° binocular field-of-view. Martin and Warner indicated this may suggest that increasing the field-of-view beyond 90° will not significantly improve pilot performance.

5.4 Scene Content

Scene content simply refers to the level of detail available for the given scene. There are varying reports on the performance advantages of greater scene detail depending on the task performed and the study. The conclusions Westra and colleagues reached with the carrier landing studies indicate scene detail had very small effects, and the helicopter shipboard landing studies indicate a range of small to large effects. Specifically, Westra et al. (1987) stated that the "largest" scene detail effects occurred during the approach, hover, and landing phases. A possible explanation for this is that the takeoff and landing tasks performed by any pilot typically require greater concentration than normal in-flight tasks.

6 Temporal Properties of Simulator Visual Systems

Temporal properties are potentially the most important aspects of a simulation (or virtual environment) system, but they are also among the most difficult to measure. Temporal properties include phosphor lag, time lag, refresh rates, and update rates, all of which we discuss below.

6.1 Phosphor Lag

When the phosphor on the CRT screen continues to glow from one frame to the next, we say that the screen exhibits *phosphor lag*. If this lag is excessive, it will cause smearing of a moving image and after-images of previous frames may be visible (AGARD, 1981). We discuss this topic further in the section on refresh rates.

6.2 Time Lag

Although *time lag* (often simply referred to as "lag") may refer to either the cockpit instruments, the motion system, or the simulator visual system, most research concerning time lag pertains to the motion and visual systems. Because the majority of information we receive is from visual stimuli, our discussion here will focus largely on the visual system. Frank, Casali, and Wierwille (1988) confirm this point as they cite Newell and Smith, who show that our reliance on visual stimuli transfers to simulators. Frank et al. (1988) later concluded that visual delay is far more disruptive to a simulator operator's control performance and physical comfort than motion delay.

At the Navy's Visual Technology Research Simulator, Westra and Lintern (1985) compared two simulator systems in their studies of helicopter landings on small ships. The two simulator systems exhibited visual lags of 217 and 117 msec, respectively. Researchers found that pilot performance was better with the shorter lag system. Curiously, although lag had only small effects on objective performance measures, pilots noticed the increased lag and believed it had a serious detrimental effect on their performance.

Uliano, Lambert, Kennedy, and Sheppard (1986) conducted another study as part of the Navy's VTRS program on three visual throughput delay systems with varying amounts of lag at 215 ± 70, 177 ± 23, and 126 ± 17 msec, respectively. Here, they concluded that lag had no effect on illness in any of the conditions. They also noted that pilots were almost unanimously aware of the two longest lags, and that simulator performance was the worst under the longest lag condition.

Westra et al. (1987) conducted a second study of helicopter landings on small ships using system visual lags of 183 and 117 msec. Once again, they concluded that the smaller system lag had only small effects on improved performance. They also concluded that the 183 msec lag system is marginally acceptable for performance and mentioned that there is a substantial accumulation of empirical evidence indicating increased lag contributes to deteriorated operator performance. After this study, they recommended a constant condition of 117 msec for future VTRS transfer-of-training research. In their paper, they cite Ricard et al., who "contrasted delays of 68 and 128 milliseconds and reported significantly lower error rates on all their measures of helicopter shipboard landing performance with the shorter delay." The Ricard study generated one display frame every 33 msec and they learned that a difference of 66 msec (two frames) produces a "just noticeable difference" in performance while the one frame delay of 33 msec is "just noticeable."

The time lag issues discussed above deal strictly with transport delay, that is, "the time period from stick input to the completion of the first field of video output" (Westra et al., 1987). Lilienthal (1992) recommended a limit on transport delays of 100–125 msec to ensure that pilot technique is not affected by the delay, asserting that large transport delays (over 150 msec) made it difficult, if not impossible, for a pilot to adapt to the system. For large transport delays, pilots could not predict with any accuracy the length of the delay and attempts to "guess and lead" the system failed. As a result, pilots would overcompensate and produce oscillations, which would cause abnormal accelerations sometimes leading to sickness.

Time lag can lead to problems beyond decreased performance and confidence. It also can lead to the "cue asynchrony problem," a problem that can contribute to simulator sickness (Lilienthal, unpublished). Lilienthal describes cue asynchrony as the difference between any two interacting systems (i.e., motion, visual, or instruments) and recommends that the delay between any two cues be less than 35 msec because "the motion cues may give the impression of motion in one direction while the delayed visual cues give the impression of motion in another direction." Kennedy, Fowlkes, and Hettinger (1989) state that there were only two experiments addressing lags and asynchronies. In the first study Uliano et al. (1986) claim no differences in sickness ratings and in the second study, Frank, Wierwille, and Casali (1988) show that transport delays affected performance (i.e., manual control) behaviors, but the size of the delay did not affect reports of simulator sickness (Kennedy et al., 1989).

6.3 Refresh Rate

Refresh rate refers to the rate at which the CRT updates the scene. Television sets in the United States, for example, operate at 30 Hz in a 2:1 interlaced mode. That is, each raster line on the screen is painted 30 times a second, such that the electron beam paints every other line during one sweep of the frame buffer, and the alternate set of lines during the next pass. The electron beam continually alternates between these sets of lines, sweeping the entire screen 60 times a second. The human visual system is generally not susceptible to flicker at 30 Hz in the fovea or central vision, however, the observer may still perceive flicker with peripheral vision. The point at which flicker becomes visually perceptible is called the *flicker fusion frequency threshold.*

Refresh rate and luminance are related factors that contribute to determining the flicker fusion frequency threshold. As the level of brightness increases, the speed of refresh must also increase in order to suppress flicker. Unfortunately, as the speed of refresh increases, the cost of the display will also increase. As a result, many users of flight simulators with slower refresh rates will reduce the visibility to dusk conditions (lower luminance) in order to prevent flicker.

Field-of-view also affects the flicker fusion frequency threshold. Since the peripheral visual system is more sensitive to motion than the central visual system, larger field-of-view displays increase the likelihood that the observer will perceive *flicker* (Lilienthal, unpublished). Once again, refresh rates must increase with larger field-of-view displays in order to suppress flicker.

Slower refresh rates require more persistent phosphors that are not suitable for displaying moving images because they will cause the images to smear (AGARD, 1981). Also, slower refresh rates promote flicker, which Van Cott (1990) cites as a contributor to simulator sickness. Lilienthal (1992) also states that flicker is distracting, induces eye fatigue, and appears to be associated with simulator sickness, and that if the cost of refresh rates are too high, then the trade-off should be made with luminance specifications.

The literature mentions two general categories of display flicker. *Small-field flicker* refers to elements in single lines or small groups of lines corresponding to the central visual system, while *large-field flicker* refers to all portions of the display and the peripheral visual system. Large-field flicker appears as random movements across the display and is more objectionable than small-field flicker (AGARD, 1981). Kennedy (1990) supports this argument and found that large-field flicker may be interpreted as motion in the background, and the discomfort reported from flicker may cause sickness.

6.4 Update Rate

While the refresh rate indicates how often the frame buffer is examined and displayed to the screen, the *update rate* refers to 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. Unlike refresh rate, which is hardware-determined, update rate can vary dramatically based on scene complexity and available computing power for the simulation.

7 Determining Susceptibility to Simulator Sickness

Havron and Butler in 1957 and Miller and Goodson in 1958 were the first pairs of researchers to mention the phenomenon of simulator sickness by name (Frank, Kennedy, Kellogg, & McCauley, 1983). Research on simulator sickness steadily increased through 1980, while by 1985, reported incidents of simulator sickness nearly doubled (Kennedy and Frank, 1985). A majority of these reports investigate the rate of incidence of simulator sickness and attempt to characterize the population that might be most susceptible to it. The reported rate of incidence varies, as Casali and Frank (1987) point out in their review of the literature, which documents incidence rates ranging from 0% to nearly 90% in flight devices and even higher in some ground vehicle devices. Kennedy et al. (1987) provide more concise results taken from U.S. Navy studies conducted over a 2-year period at 10 flight simulator sites. These studies showed less variation, with incidence rates ranging from 12 to 60% in these simulators.

Several studies have attempted to determine whether certain individuals or groups were more susceptible to simulator sickness than others. For example, Kennedy et al. (1987) claim that "perhaps as much as 80% of the simulator sickness problem resides in perhaps 20% of the population." They later went on to say that "only about 30% of the individuals become ill under even the worst simulator conditions." In an attempt to isolate various individual sources, Kennedy and Frank (1985) address several, including gender, age, and physiological condition.

7.1 Gender

Regarding *gender,* Kennedy and Frank (1985) claim that women are more susceptible to motion sickness than men. They mention a postulate concerning motion sickness which stated "that perhaps hormonal influences are at play, since women are most susceptible during their menstrual cycle." Perhaps more importantly, they noted that women exhibit larger fields of view than men, and it is a well documented fact that simulator sickness appears more prevalent in simulators with wide fields of view.

7.2 Age

Kennedy and Frank (1985) address *age* as a factor and state that susceptibility is highest for individuals from about 2 years of age through puberty. Susceptibility to simulator sickness decreases rapidly up through age 21, then decreases gradually thereafter, and finally disappearing almost entirely at age 50.

7.3 Illness

Illness is another factor that increases a person's susceptibility to simulator sickness. Previously, Frank et al. (1984) addressed the physiological state of the individual and advised against using the simulator if the subject were ill or suffered from fatigue, sleep loss, hangover, upset stomach, periods of emotional stress, head colds, ear infection, ear blocks, upper respiratory illness, or if the subject were taking some kinds of medication. They further recommend not using simulators more than necessary when suffering from the effects of flu or possibly after receiving a flu shot, primarily because the literature on motion sickness and vomiting shows that the symptoms of flu and simulator sickness are cumulative (Frank et al., 1984).

7.4 Position in the Simulator

Casali and Wierwille (1986) looked at crewmember susceptibility and found that susceptibility to simulator-induced sickness can be a function of the aircrew member's *degree of control* in the simulator cockpit. This could explain why the incidence of simulator sickness among pilots is lower than that of co-pilots or other crewmembers; pilots generally control more of the motion and visuals than the other members of the flight crew. Lackner (1990) found that when subjects generated input themselves they were less susceptible to motion sickness. He makes the point that the person controlling or anticipating the motion becomes sick less often than the passengers, a phenomenon similar to the experiences of many automobile passengers whose car sickness diminishes or disappears when they are the driver.

7.5 Pilot Experience

The level of *previous experience* is another factor relevant to determining whether any given individual will be prone to simulator sickness. Kennedy et al. (1987) believe that experienced pilots have greater difficulty than novice pilots and they cite research done in the field from 1957 to the present to support their argument. Specifically, they state that Miller and Goodson (1960) found 60% of the instructor pilots reported symptoms as compared to only 12% of the student pilots, and McGuiness et al. (1981) concluded that the more experienced aircrews (over 1500 flight hours) had a higher incidence of symptoms than the less experienced flight crew. On the other hand, Magee, Kantor, and Sweeney (1987) stated there was no evidence to indicate that experience influenced susceptibility to simulator sickness.

These seemingly contradictory conclusions come from the inconsistent definitions for "novice pilot." This issue came up at the 1988 Advisory Group for Aerospace Research and Development (AGARD) conference during the concluding roundtable discussion. In the Magee et al. (1987) study, "novice pilots" were defined as those who were new to the C-130 aircraft, but averaged 1500 flight hours, while previous studies defined novice pilots as those who had little or no total flight time. The outcome of the discussion was that the AGARD committee generally accepted "novice" to mean little or no flight experience. As a result, the committee recognized that more experienced pilots tend to experience greater difficulty than novices, and that the different criterion used explained the varying results.

The fact that experienced pilots have greater difficulty might be explained from several points already mentioned. Since more experienced pilots have clearer expectations than novices of what should happen in the real aircraft, an incorrect simulator signal to the experienced individual may result in a greater mismatch discrepancy than for the novice. Further, since student pilots tend to handle the flight controls more than the instructor pilots, they may be less susceptible because they control the input to the system. Finally, if the optimal position is placed at the student pilot's location, this would be one explanation for the higher incidence rates for instructor pilots.

8 Theories

After examining several generic sources for individual differences in susceptibility, Kennedy and Frank (1985) reviewed a number of theories that attempted to explain the origin of motion sickness. The most popular of these theories, the "perceptual conflict" theory proposed by Steele in the '60s, is also known as the "sensory conflict" theory or the "cue-conflict" theory. This theory addresses the mismatch between signals that the visual or vestibular system is getting from the simulator and the signals the pilot is expecting to get based on his or her previous experience. Van Cott (1990) described this theory as sickness that arises when "motion information from vision, the vestibular system, and proprioceptors (sensory receptors) may be in conflict with the expected values of these inputs derived from past experience." Although this theory does not answer every possible source of simulator sickness, it is presently the most widely accepted working model explaining the illness. Cheung, Howard, and Money (1991) support the Kennedy and Frank conclusions concerning the vestibular system and simulator sickness, and their conclusions are consistent with the theory of sensory conflict.

9 The Disadvantages of Simulator Use

9.1 After-Effects

The debilitating effects of a simulator can last far beyond the simulator session itself. If an individual experiences side-effects (pallor, sweating, nausea) as the result of a simulator session, the consequences of operating another vehicle such as a car or the actual aircraft after simulator exposure could be hazardous. Many of the reports on simulator after-effects include examples where the user receives a conflict from the orientation cues used in the simulator. Kennedy et al. (1987) tell of an incident where one individual had to stop his car on the side of the road because the pronounced after-effects of a particularly intense simulator experience. Kellogg, Castore, and Coward (1980) cited F-4 pilots reporting delayed perceptual after-effects occurring 8 to 10 hr following simulator flight. These observations led to additional studies that attempted to better understand the issues of after-effects.

In one of four studies conducted with helicopter simulators, Gower et al. (1987b) revealed that nearly 40% of the AH-64 (Apache) helicopter pilots reported symptoms lasting over an hour, and 14% reported symptoms lasting longer than 6 hr. In another study of UH-60 (Black Hawk) pilots, Gower and Fowlkes (1989) reported cases where individuals experienced delayed effects for over 24 hr after exposure. They concluded that approximately 8% of the aviation population experiences delayed problems beyond the simulator session for periods that exceed 6 to 8 hr, and an even smaller population will experience symptoms for as long as 1 to 2 days. As a result of this study, many U.S. Army aviation units adopted a policy that prohibits aircraft flying within 6 hr after simulator flight.

9.2 Fatigue

Frank et al. (1984) mention something they call *fatigue-decreased proficiency,* which is caused by simulator sickness symptoms causing distractions that interfere with learning or by being fatigued upon entry to the simulator. Ebenholtz (1990) claims that once the user experiences fatigue, the potential for positive learning effects from the simulator is decreased. Hamilton, Kantor, Heslegrave, Magee, and Hendy (1989) showed that over 50% of tested aircrews experienced increases in simulator sickness symptom frequency following training, with the most commonly reported symptoms being mild mental fatigue, physical fatigue, eye strain, and after-sensations of motion. The CH-47 (Chinook) Flight Simulator study conducted by Gower and Fowlkes (1989) also showed eyestrain and headache as the leading symptoms of *asthenopia,* a term optometrists use to refer to many eyestrain problems.

9.3 Adaptation

The capability of humans to adapt to simulation deficiencies, sometimes called *perceptual adaptation,* can be a problem. It is possible that an individual might use techniques to avoid simulator sickness that may be detrimental if they transfer these techniques to the actual aircraft. For example, many pilots restrict their head movement while in the simulator to avoid what is known as the *pseudo-coriolis effect.* This effect is analogous to the Coriolis force that deflects moving objects (such as projectiles or air currents) to the right in the northern hemisphere and to the left in the southern hemisphere. If a pilot moves his head rapidly during a maneuver in which the simulator is undergoing some kind of angular motion, these same coriolis-type forces begin to act on the vestibular apparatus of the inner ear, causing disorientation and discomfort. Even if the simulator remains still, "head movements during visually represented angular motion can cause pseudo-coriolis effects" (Van Cott, 1990).

Lackner (1990) also discussed how provocative the effects of head movement can be, but if pilots begin to restrict head movements, they may develop negative habits that may be detrimental if transferred to in-flight conditions. Any pilot who learns to restrict his head movement in the simulator will develop bad habits that will impact his basic flying skills and his ability to establish visual contact with other aircraft. Needless to say, this could have disastrous consequences in a battlefield scenario involving enemy aircraft.

All these negative side effects may cause some pilots to avoid simulators altogether (Frank et al., 1983). If simulators produce unpleasant side effects, they may not be used because people will lack confidence in the training they receive. The effort to produce the most realistic simulator continues to be an active area of research.

10 Conclusion

Our goals with this paper was to collect references to significant results obtained by the simulator research community. We were surprised at the current isolation between the academic computer science community and the (primarily military) simulator community, and we have collected these results, and provided our bibliography in the hopes that as virtual environments research progresses, the computer science community will be able to learn from these results, rather than reestablish them unnecessarily.

Acknowledgments

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Bibliography

AGARD. (1981). Characteristics of flight simulator visual systems. *Advisory Group for Aerospace Research and Development,* no. 164, p. 90. Neuilly sur Seine, France, May.
A key article by various authors discussing the characteristics of flight simulator visual systems. Emphasis is placed on the energy, spatial, and temporal properties of the display.

Allan, J., Buffardi, L., & Hays, R. (1991). The relationship of simulator fidelity to task and performance variables. ARI Research Note 91-58 (AD-A238 941), p. 96, George Mason University, Fairfax, VA, June.
This paper stresses that simulator fidelity should not be considered a single uniform concept, but a multidimensional one consisting of at least a physical and functional component.

Andersen, G. J. (1986). Perception of self-motion: Psychophysical and computational approaches. *Psychological Bulletin,* no. 99, 52–65.
A very technical paper that identifies two types of induced motion: rotation and translation. Two areas of research concerned with this interaction were discussed—the study of the reflex eye movement systems that are activated by visual or vestibular stimulation, and the study of how conflicting information from the visual and vestibular systems result in motion sickness.

Andersen, G. J., & Braunstein, M. L. (1985). Induced self-motion in central vision. *Journal of Experimental Psychology. Human Perception and Performance,* no. 11, 122–132.
Results presented in this paper indicate that the focal/ambient theory of induced self-motion may need to be reevaluated. An increase in induced self-motion occurs with increased velocity of the simulated terrain, a result that is inconsistent with existing peripheral vision studies. The results of this paper also failed to support the conclusion from previous research that visual induction of self-motion requires a large area of stimulation that necessarily involves the peripheral visual field. This paper also presents strong evidence that self-motion can be reliably induced from stimulation of the central visual field with a radially expanding depth pattern. The authors propose an extension to the theory of two modes of visual processing. The new claim is that ambient processing is served by a primitive visual system in the sense that it is primarily sensitive to low spatial frequencies. The authors conclude that the addition of inconsistent motion to a display should reduce the perception of self-motion.

Ayres, A., Hays, R. T., Singer, M. J., & Heinicke, M. (1984). An annotated bibliography of abstracts on the use of simulators for Technical Training. (AD-A156 792), p. 555, Fairfax, VA, October.
This article was used as a pointer to other references on the transfer of training skills from simulators to real aircraft.

Barrette, R., Dunkley, K., Kruk, R., Kurts, D., Marshall, S., Williams, T., Weissman, P., & Antos, S. (1990). Flight simulator: Advanced wide field of view, helmet-mounted, infinity display system. AFHRL-TR-89-36, p. 232. Williams AFB, AZ, September.
Results in this report were "descriptive and qualitative" rather than quantitative in nature. Citings in this report include 30 Hz motion causes sickness, whereas 60 Hz does not. Stereo vision was superior to nonstereo vision. Wider fields-of-view (FOV) were preferred, but did not necessarily result in better performance than narrow FOVs. High resolution significantly better than low resolution. Binocular detection ranges were significantly better than monocular ranges. Whole section on the impact of luminance.

Benson, A. J. (1987). Aetiological factors in simulator sickness. *AGARD Conference Proceedings No. 433 Motion Cues in Flight Simulation and Simulator Induced Sickness,* Advisory Group for Aerospace Research and Development (AGARD), Neuilly Sur Seine, France, September–October.
This paper presents the argument that simulator sickness can be induced through a "mismatch" between concomitant inputs provided by the angular and linear acceleration transducers of the vestibular apparatus, or between visual and vestibular inputs.

Berbaum, K. S., & Kennedy, R. S. (1985). An analysis of visual tasks in helicopter shipboard landing. EOTR-85-7 (AD-A161 101), p. 57, 1 November.
This study goes hand-in-hand with the Westra and Lintern 1984 study. Here, the researchers used a protocol analysis technique for linking real images to virtual images. This caused several problems: (1) all persons may not use the same visual information in performing a simulator task and

(2) the salience of specific sources of visual information might not be the same in novice pilots. This study may not reveal the use of visual information important for performance of the task that pilots do not consciously attend. The authors also discuss "augmented feedback," which is supplementary visual information not available in the real world. Five different visual cues were used for hover: motion parallax, interposition, shape consistency, peripheral vision in support of shape constancy, and spatial orientation and depth perception.

Berbaum, K. S., & Kennedy, R. S. (1985). Plan for evaluation of the training potential of helmet-mounted display and computer-generated synthetic imagery. (AD-A160 299), p. 53. Orlando, FL, April 29.
Description of a research plan to evaluate training effectiveness of a helmet-mounted display. Two computer-image generation (CIG) channels are incorporated that present wide-angle, low-resolution, low-detail background and area of interest of high resolution and detail.

Billman, E. R. (1987). The role of adaptive supplemental visual cuing in flight simulation. (AD-A185 932), p. 49. University of Illinois, Urbana, IL.
It is apparent from the work done here that flying an aircraft cannot be reduced to simple two-axis tracking.

Bridgeman, B., & Stark, L. (1991). Ocular proprioception and efference copy in registering visual direction. *Vision Research,* no. V0031 N11, 1903–1913.
The results obtained in this experiment showed efference copy to be the dominant source of information that informs both perception and visually guided behavior. Proprioception did not have an effect, at least in perception, but the slope of the proprioception function was very shallow—a large change in eye position resulted in only a small change in the proprioception signal. The function of proprioception in perception and visual–motor coordination, then, seems to be as a backup for the principal influence of efference copy signals, though it provides a significant supplement to the registration of eye position.

Caldwell, J. L., Cornum, R. L., Stephens, R. L., & Rash, C. E. (1990). Visual processing: Implications for helmet mounted displays. (AD-A223 488), p. 8. United States Army Aeromedical Research Laboratory, Fort Rucker, AL, May.
A study was conducted to compare the performance of AH-64 (Apache) pilots to other Army pilots on visual tasks. Each pilot was presented the scene monocularly to the right eye. Results indicated no performance difference between groups of pilots on the dichoptic task, but indicated better performance on the left monocular task for the AH-64 pilots.

Cardullo, F. M. (1992). *Motion and Force Cuing II,* Flight Simulation Update—1992, SUNY Binghampton–Watson School of Engineering, Binghampton, NY, Jan(6–10).
Good background regarding simulators in general. Good discussion on the physiological effects of high G flight.

Caro, P. W. (1972). Transfer of instrument training and the synthetic flight training system. (AD-743 155), p. 9. Human Resources Research Organization, Alexandria, VA, March.
Hard results regarding transference of skill data for flight simulators.

Caro, P. W. (1973). Aircraft simulators and pilot training. *Human Factors, 15*(6), 502–509. Human Resources Research Organization, Alexandria, VA.
This study refers to his 1972 study demonstrating transfer of training.

Caro, P. W. (1976). *Some factors influencing transfer of simulator training.* Presented at Third Flight Simulation Symposium of the Royal Aeronautical Society, p. 18. Human Resources Research Organization, Alexandria, VA, April.
Transfer of training has not yet received the systematic attention it warrants. "The lack of evidence of visual display training effectiveness cannot be taken as evidence of their lack of effectiveness."

Caro, P. W. (1977). Factors influencing simulator training effectiveness in the U.S. Air Force. HumRRO FR-ED-77-18 (AD A043 119), p. 11. Human Resources Research Organization, Alexandria, VA, July.
It was found that programs had not been subjected to formal evaluation studies that would establish their training effectiveness in quantitative terms.

Caro, P. W. (1977a). Some current problems in simulator design, testing and use. HumRRO PP-2--77 (AD A043 240), p. 14. Human Resources Research Organization, Alexandria, VA, March.

Caro, P. W. (1977b). Aircraft simulators and pilot training. HumRRO PP-6-74 (AD A002 614), p. 11. Human Resources Research Organization, Alexandria, VA, March.
A study of transference of skill in flight simulators. There was a 90% reduction in the amount of aircraft time required to attain course objectives. Impressive training benefits were shown when the trainer was used in conjunction with a training program incorporating the training features described above.

Casali, J. G. (1985). Vehicular simulator-induced sickness,

Vol. I. NTSC-TR86-010 (AD-A173 904), p. 92. Naval Training Systems Center, Arlington, VA, 31 August.
Report provides a background information on the sickness problem. The majority of the report comprises a literature review specific to simulator sickness. Most simulators incorporate displays that are biocular. The higher the scene detail, the greater the stimulation evidencing movement and vection and the greater the likelihood of a conflict with attenuated vestibular cues in the simulator.

Casali, J. G., & Rosech, R. J. (1986). Vehicular simulator-induced sickness. NTSC-TR86-011 (AD-A172 990), p. 39. Naval Training Systems Center, Arlington, VA, 31 August.
This report includes bibliographic listings and abstracts for those references that have direct mention of or close association with simulator sickness.

Casali, J. G., & Wierwille, W. (1986). Vehicular simulator-induced sickness, Volume III. NTSC-TR86-012 (AD-A173 226), p. 155. Naval Training Systems Center, Arlington, VA, August.
This paper shows that in terms of the display system, the use of folded reflective optics appears relatively straightforward and versatile, but the CRTs may be at the edge of the state of the art. Also discussed is how crewmember susceptibility to simulator sickness may largely be a function of the aircrew member's position in the simulator cockpit. More experienced pilots are more susceptible to simulator-induced sickness.

Casali, J. G., & Frank, L. H. (1987). Manifestation of visual/vestibular description in simulators: Severity and empirical measurement of symptomatology. *AGARD Conference Proceedings No. 433 Motion Cues in Flight Simulation and Simulator Induced Sickness.* Advisory Group for Aerospace Research and Development (AGARD), Neuilly Sur Seine, France, September–October.

Chambers, W. S. (1992). *Visual System Overview,* Flight Simulation Update—1992, SUNY Binghampton–Watson School of Engineering, Binghampton, NY, Jan(6–10).
This paper concentrates on discussions of perception and visual image processing.

Chappelow, J. W. (1987). Simulator sickness in the Royal Air Force. *AGARD Conference Proceedings No. 433 Motion Cues in Flight Simulation and Simulator Induced Sickness.* Advisory Group for Aerospace Research and Development (AGARD), Neuilly Sur Seine, France, September–October.
Contains a discussion of the prevalence of simulator sickness in the Royal Air Force.

Cheung, B. S. K., Howard, I. P., & Money, K. E. (1991). Visually-induced sickness in normal and bilaterally labyrinthine-defective subjects. *Journal of Aviation, Space, and Environmental Medicine,* No. 62, 527–531.
Results in this paper show that labyrinthine-defective subjects experience no sickness symptoms, which strongly suggests that the vestibular system is necessary for sickness induced by moving visual fields. Findings are in agreement with the sensory conflict theory, that motion sickness symptomatology may be produced when patterns of visual, vestibular, and somesthetic stimulation are at a variance with a neural store of expectations based on past experience.

Crosby, J. V., Pohlman, L. D., Leshowitz, B., & Waag, W. L. (1978). Evaluation of low fidelity simulator (LFS) for instrument training. (AD-A058 139), p. 14. HQ Air Force Human Resources Laboratory, Tempe, AZ, July.
LFS trained group performed significantly better than the control group across all maneuvers. Analysis of the collected data during T-4 training revealed significantly fewer trials to criterion for the experimental groups. On the second ASPT sortie, however, no differences were found between the groups. Likewise, the data collected during the T-3 training revealed no differences. The results indicated a considerable amount of positive transfer at the onset of the UPT program. These initial performance differences, however, appeared to wash out following approximately one month of academic and T-4 simulator training. Beyond this point, no differences between the groups could be detected.

Cross, K. D., & Gainer, C. A. (1987). An enumeration of research to determine the optimal design and use of Army flight training simulators. Technical Report 763 (Ad-A191 242), p. 207. US Army Research Institute for the Behavioral and Social Sciences, Fort Rucker, AL, October.

Cullen, J. K., Rampp, R. D., May, J. G., & Dobie, T. G. (1990). Measures of auditory evoked potentials during optokinetic stimulation. NBDL-87R005 (AD-A232 722), p. 4. Naval Diodynamics Laboratory, New Orleans, LA, 1 October.
Current theory holds that motion sickness results from a mismatch in information derived from the sensory organs involved in the balance and maintenance of spatial position. The results of this experiment suggest that optokinetic stimulation, with or without induction of motion sickness, tends to alter the interwave interval of click-evoked auditory brainstem responses.

Daunton, N. G., Fox, R. A., & Crampton, G. H. (1984). Susceptibility of cat and squirrel monkey to motion sickness induced by visual stimulation: Correlation with susceptibility to vestibular stimulation. *AGARD Conference Proceedings No. 372—Motion Sickness: Mechanisms, Prediction, Prevention and Treatment.* Advisory Group for Aerospace Research and Development (AGARD), Neuilly Sur Seine, France, May.

Dixon, K. W., & Curry, D. G. (1990). Weapons delivery training: Effects of scene content and field of view. AFHRL-TP-88-29 (AD-A227 968), p. 17. Operations Training Division, Williams AFB, TX, November.

Research here shows that neither the scene content nor the FOV variable affected the number of trials to reach proficiency. Even though there were no strong and consistent effects in bomb scores, the overall performance of subjects was better in training conditions that incorporated familiar objects. There was also better performance for full-FOV display. This leads us to believe that tasks requiring close adherence to a flight profile should use full-FOV displays and incorporate vertically developed cues.

Dizio, P. (1991). Motion sickness susceptibility in parabolic flight and velocity storage activity. *Aviation Space and Environmental Medicine,* no. V0062 N4, 300–307.

This paper attempts to identify potential links between vestibular processing of head movements and space motion sickness.

Dobie, T. G. (1991). Teaching the right stuff—the heart of the matter. NBDL-90R017 (AD-A232 766), p. 5. Naval Biodynamics Laboratory, New Orleans, LA, January.

The major findings of this paper support the contention that cognitive-behavioral training provides significant therapeutic benefit for individuals who are highly susceptible to visually induced motion sickness. Cognitive treatment alone, although less effective, provided significant improvement. On the other hand, desensitization alone showed virtually no change. This argues for the importance of counseling approach in the treatment of motion sickness.

Dobie, T. G., May, J. G., Fisher, W. D., & Elder, T. (1990). A comparison of two methods of training resistance to visually-induced motion sickness. NBDL-87R004 (AD-A231 806), p. 11. Naval Biodynamics Laboratory, New Orleans, LA, 1 October.

The findings of this study support the efficacy of cognitive-behavioral therapy for increasing tolerance to stimulation that elicits motion sickness. Although cognitive-behavioral therapy procedures resulted in significant increases in tolerance, the precise reason for this is not clear.

Dobie, T. G., May, J. G., Fisher, W. D., & Bologna, N. B. (1990a). An evaluation of cognitive-behavioral theory for training resistance to visually-induced motion sickness. NBDL-87R008 (AD-A231 807), p. 11. Naval Biodynamics Laboratory, New Orleans, LA, 1 October.

The major finding in the present report supports the contention that the cognitive-behavioral treatment provides significant therapeutic support for individuals who are highly susceptible to visually induced motion sickness. The results suggest that it is not the cognitive or desensitization alone that increases resistance to visually induced disorientation, but the combination that is most effective.

Dobie, T. G., May, J. G., Dunlap, W. P., & Anderson, M. E. (1990b). Reduction of visually-induced motion sickness elicited by changes in illumination wavelength. NBDL-89R009 (AD-A232 860), p. 11. Naval Biodynamics Laboratory, New Orleans, LA, 1 October.

This experiment was undertaken to assess the degree of stimulus generalization in visually induced motion sickness. The most interesting finding was the change in motion sickness estimates within a session before and after color change. The increase within a session was greater before change than after. The authors speculate that if a change in the wavelength of the illumination used during VM stimulation results in a reduction in the rate at which motion sickness develops, then perhaps color changes in motion environment might increase motion sickness tolerance in real world settings.

Dobie, T. G., & May, J. G. (1990). Generalization of tolerance to motion environments. NBDL-90R010 (AD-A232 766), p. 8. Naval Biodynamics Laboratory, New Orleans, LA, 1 October.

The major finding of the present study provides some support for the belief that tolerance acquired using one device can transfer to another motion experience. The finding that cognitive counseling in combination with visually induced apparent motion affords considerable tolerance for that sort of stimulation is in agreement with previous reports.

Ebenholtz, S. (1990). Oculomotor factors and design requirements. *Motion Sickness, Visual Displays, and Armored Vehicle Design,* pp. 18–27. Ballistic Research Laboratory, APG, MD, Washington, DC, April.

Very good explanation of asthenopia and why/how these stresses affect pilots as they do. Article gives good background as far as physiological issues and fatigue.

Evans, R. M., Scott, P. G., & Pfeiffer, M. G. (1984). SH-3 helicopter flight training: An evaluation of visual and motion simulation in device 2F64C. Technical Report 161 (AD-B090 118), p. 46. Naval Training Equipment Center, Orlando, FL, December.

Regardless of the device feature employed, the 2F64C flight simulator significantly reduces the number of flights, flight time, and trials-to-mastery for training pilots to fly the SH-3 helicopter. Transfer ratios, averaged across the three criterion measures, resulted in the best transfer of training under visual and motion conditions, and about equal transfer for motion only and no-visual/no-motion groups.

Frank, L., Kennedy, R. S., Kellogg, R. S., & McCauley, M. E. (1983). Simulator sickness: A reaction to a transformed perceptual world: I. Scope of the problem. (AD-A192 438 (NAVTRAEQUIPCENT-65)), p. 10. Orlando, FL, April 29.
A discussion of incidence of simulator sickness in a variety of military flight simulators.

Frank, L., Kennedy, R. S., McCauley, M. E., Root, R. W., Kellogg, R. S., & Bittner, A. C. (1984). Simulator sickness: Sensiomotor disturbances induced in flight simulators. *The Image II Conference Proceedings Held at Phoenix AZ,* pp. 417–426. Williams AFB, AZ, 30 May–1 June.

Frank, L. H., Casali, J. G., & Wierwille, W. (1988). Effects of visual display and motion system delays on operator performance and uneasiness in a driving simulator. *Human Factors,* no. 30, 201–217.
Visual delay appears to be more disruptive to an individual's control performance and well-being than motion delay.

Ancman, E. G. (1991). Perpetual limitations of peripherally displayed colors on CRT's. (AD-A236 289), p. 43. Wright Laboratory, Wright Patterson AFB OH, March.
The results of this study will be used to determine the best cockpit format color usage for retrofit and future aircraft designs.

Gibson, R. S., & Orlansky, J. (1986). Performance measures for evaluating the effectiveness of maintenance training. IDA Paper P-1922 (AD-A175 351), p. 75. Institute for Defense Analysis, Alexandria, VA, September.
This paper argues that the interpretation of any training effectiveness evaluation of a simulated maintenance trainer depends in part on an understanding of the device's behavioral fidelity on critical tasks.

Gillingham, K. K., & Wolfe, J. W. (1986). Spatial orientation in flight. USAFSAM-TR-85-31 (AD-A183 431), p. 134. USAF School of Aeromedicine, Brooks AFB, TX, December.
Good description of physiological issues involved in spatial orientation.

Gower, D. W., & Fowlkes, J. E. (1989a). Simulator sickness in the AH-1S (Cobra) flight simulator. USAARL 89-20 (AD-A214 562), p. 76. U.S. Army Aeromedical Research Laboratory, Fort Rucker, AL, September.
This report ranks the Army's flight simulators in comparison to the 10 Navy simulators studied by the NTSC, Orlando, FL.

Gower, D. W., & Fowlkes, J. E. (1989b). Simulator sickness in the UH-60 (Black Hawk) flight simulator. USAARL 89-20 (AD-A214 434), p. 74. U.S. Army Aeromedical Research Laboratory, Fort Rucker, AL, September.
This report ranks the Army's flight simulators in comparison to the 10 Navy simulators studied by the NTSC, Orlando, FL. Discussion same as Apache, Chinook, and Cobra results. Some cases reported where those using this simulator experienced delayed effects over 24 hr after exposure.

Gower, D. W., Lilienthal, M. G., Kennedy, R. S., & Fowlkes, J. E. (1987a). Simulator sickness in US Army and Navy fixed- and rotary-wing flight simulators. *AGARD Conference Proceedings No. 433 Motion Cues in Flight Simulation and Simulator Induced Sickness.* Advisory Group for Aerospace Research and Development (AGARD), Neuilly Sur Seine, France, September–October.
Data pooled from 10 Navy simulators and the Apache CMS.

Gower, D. W., Lilienthal, M. G., Kennedy, R. S., Fowlkes, J. E., & Baltzey, D. R. (1987b). Simulator sickness in the AH-64 Apache combat mission simulator. USAARL 88-1 (AD-A193 419), p. 49. U.S. Army Aeromedical Research Laboratory, Fort Rucker, AL, November.
This series of studies references the previous work done by the U.S. Navy and includes the findings that emerged (p. 5). Results are consistent with the Navy's findings. Study focused on the long-term effects of simulator sickness and the length of time of after-effects.

Gower, D. W., Fowlkes, J. E., & Baltzey, D. R. (1989). Simulator sickness in the CH-47 (Chinook) flight simulator. USAARL 89-28 (AD-A218 214), p. 69. U.S. Army Aeromedical Research Laboratory, Fort Rucker, AL, September.
This series of studies references the previous work done by the U.S. Navy and includes new findings consistent with the Navy's. Study brought up the issue of eyestrain and headache as the leading symptoms of asthenopia. Mentions the Army policy of a 6-hr wait period.

Hale, S. (1987). Helicopter external vision requirements and visual display characteristics: A report/bibliography. Technical Note 6-87 (AD-A187 075), p. 25. U.S. Army Human Engineering Laboratory, Aberdeen Proving Ground, Maryland, October.
This literature search contains several pointers to other papers indicating the strengths of wider field of view and bin-

ocular presentation over narrower field of view and monocular presentation.

Hale, S. (1990). Visual accommodation and virtual images: A review of the issues. EFR-029 (AD-B141 629), p. 23. U.S. Army Human Engineering Laboratory, Aberdeen Proving Ground, Maryland, February.
This article discusses the central issue of the compatibility question, namely, visual accommodation to virtual images. A discussion on monocular versus binocular vision.

Hamilton, K., Kantor, L., Heslegrave, R., Magee, L., & Hendy, K. (1989). Simulator induced sickness in the CP-140 (Aurora) flight deck simulator. DCIEM No. 89-RR-32 (AD-A213 096), p. 20. Defense and Civil Institute of Environmental Medicine (Canada), Downsview, Ontario, May.

Hebb, R. C., Hennessy, R. T., Lintern, G., & Collyer, S. C. (1981). Unconventional visual displays for flight training. Government Document AD-A111 39 p. 62. Naval Training Equipment Center, Orlando, FL, November.
The general purpose of the research reported here was to examine training effectiveness for basic flight tasks of radically different methods of displaying the information that is necessary to support learning of the tasks. Pretraining with experimental displays resulted in substantial transfer savings to the control display. The hypothesis that control skills can be learned using representations of essential information that depart radically from the form found in natural scenes was supported by the results. Field of view did not importantly affect training or transfer performance of the straight and level task.

Holman, G. L. (1979). Training effectiveness of the CH-47 flight simulator. (AD-A072 317), p. 82. U.S. Army Aviation Center, Fort Rucker, AL, May.
The authors of this paper concluded that the Ch-47 flight simulator is an effective training device for all maneuvers tested except for those, such as hovering maneuvers, that require extensive visual ground referencing at very low altitudes. The simulator was also found to be inadequate for training night operations and terrain flying.

Howard, L. P., Cheung, B., & Landolt, J. P. (1987). Influence of vection and body posture on visually-induced self-rotation and tilt. *AGARD Conference Proceedings No. 433 Motion Cues in Flight Simulation and Simulator Induced Sickness.* Advisory Group for Aerospace Research and Development (AGARD), Neuilly Sur Seine, France, September–October.
Studied vection and illusory body tilt under six conditions. Yaw vection around the vertical axis was strongest. Forward pitch vection was stronger than backward pitch vection. Contrary to previous reports, for most subjects backward illusory tilt was much stronger than forward illusory tilt.

Hyman, A. (1990). Concepts for display interface for battlefield commanders. *Motion Sickness, Visual Displays, and Armored Vehicle Design,* pp. 3–17. Ballistic Research Laboratory, APG, MD, Washington, DC, April.

Isley, R. N., & Spears, W. D. (1982). Phase I pilot study: VTRS transfer of training experiment. Seville TR 82-03 (Ad-A120 315), p. 44. Naval Training Equipment Center, Orlando, FL, March.

Johnson, K. L., & Bogumill, M. P. F-16 & A-10A OFT simulators flight system development and test. (AD-P000 214), pp. 485–492.
This paper contends that the greatest amount of transfer of training for flight systems operation and performance is obtained with a design philosophy that replicates cockpit features, visual cues, and the performance of the actual aircraft. The authors believe that the high fidelity flight performance and dynamics are necessary but not sufficient for high transfer of training.

Kaempf, G. L., Cross, K. D., & Blackwell, N. J. (1989). Backward transfer and skill acquisition in the AH-1 flight and weapons simulator. ARI Research Report 1537 (AD-A213 432), p. 48. Army Research Institute for Behavioral and Social Sciences, Fort Rucher, AL, August.

Kellogg, R. S., Castore, C., & Coward, R. (1980). Psychophysiological effects of training in a full vision simulator. *Annual Scientific Meeting of the Aerospace Medical Association.*

Kellogg, R. S., Kennedy, R. S., & Woodruff, R. R. (1984). Comparison of color versus black-and-white visual displays as indicated by bombing and landing performance in the 2B35 TA-4j flight simulator. *The Image II Conference Proceedings Held at Phoenix AZ,* p. 18. Williams AFB, AZ, July.
Under conditions of the study, no statistically significant differences were shown between performance with color or with black-and-white. It is concluded that color visual scene presentation, within the limits of this R&D, does not enhance performance.

Kennedy, R. (1990). Reconsidering human factors engineering criteria for armored vehicle design. *Motion Sickness, Visual Displays, and Armored Vehicle Design,* pp. 51–63. Ballistic Research Laboratory, APG, MD, Washington, DC, April.

Kennedy, R. S., & Frank, L. H. (1985). A review of motion sickness with special reference to simulator sickness. (AD-A155 975), p. 45. Canyon Research Group, Inc., Westlake Village, CA, 15 April.

Title says it all: includes an examination of low frequency motion for simulators. Also studied here is the effect of body sway, sleep loss, illness, gender, and age. Includes a discussion of perceptual conflict theory, fear/anxiety theory.

Kennedy, R. S., Frank, L., & McCauley, M. E., Bittner, A. C., Root, R. W., & Binks, T. A. (1984a). Simulator sickness: Reaction to a transformed perceptual world VI. Preliminary site surveys. *The Aerospace Medical Panel Symposium on Motion Sickness: Mechanisms, Prediction, Prevention, and Treatment at Williamsburg, Virginia on 3–4 May 1984,* p. 11, May.

Kennedy, R. S., Frank, L., & McCauley, M. E. (1985). Simulator sickness: Reaction to a transformed perceptual world II. Sourcebook and suggested readings. AD-A210 512, p. 322.

This paper traces the history of the phenomenon of simulator sickness from the time it was first reported in 1957–1958.

Kennedy, R. S., Berbaum, K. S., Hettinger, L. J., & Dunlap, W. P. (1986). Short-term solutions to prevent simulator induced motion sickness: Report of a conference. EOTR-87-6 (AD-A187 275), p. 194, March.

Kennedy, R. S., Berbaum, K. S., Lilienthal, M. G., Dunlap, W. P., Mulligan, B. F., & Funaro, J. F. (1987a). Guidelines for alleviation of simulator sickness symptomatology. (NAVTRASYSCEN TR-87007) (AD-A182 554 (NAVTRASYSCEN TR-87007)), p. 68, March.

An excellent paper covering the incidence of simulator sickness in military pilots and the possible causes and contributing factors.

Kennedy, R. S., Berbaum, K. S., Allgood, G. O., Lane, N. E., Lilienthal, M. G., & Baltzey, D. R. (1987b). Etiological significance of equipment features and pilot history in simulator sickness. *AGARD Conference Proceedings No. 433 Motion Cues in Flight Simulation and Simulator Induced Sickness.* Advisory Group for Aerospace Research and Development (AGARD), Neuilly Sur Seine, France, September–October.

A survey of 10 flight trainers where performance tests were administered. Several findings emerged including simulator sickness incidences varied from 10 to 60%.

Kennedy, R. S., Berbaum, K. S., & Collyer, S. C. (1988). Spatial requirements for visual simulation of aircraft at real-world distances. *Human Factors,* no. 30, 153–61.

In flight training simulators, with high resolution, luminance contrast of 25:1 produced better performance than lower contrasts.

Kennedy, R. S., Fowlkes, J. E., & Hettinger, L. J. (1989). Review of simulator sickness literature. NTSC TR89-024, p. 51. Orlando, FL, 4 September.

Most current review of simulator sickness literature of the Navy's 10 simulator sites and other U.S. Army and Coast Guard simulators using the same criteria for measurements.

Kottas, B. L., & Bessemer, D. W. (1980). Comparison of potential critical feature sets for simulator-based target identification training. (AD-A128 344), p. 103. U.S. Army Institute for the Behavioral and Social Sciences, Fort Knox, KY, September.

The authors conclude that highly detailed vehicle representations are necessary for target identification training.

Lackner, J. (1990). Human orientation, adaptation, and movement control. *Motion Sickness, Visual Displays, and Armored Vehicle Design,* pp. 28–50. Ballistic Research Laboratory, APG, MD, Washington, DC, April.

Lackner discusses the vestibular issues of motion sickness in depth. Includes a discussion of the effects of head movement and how provocative they can be. Also discusses the issue of the problem of visual displays when there are moving elements in the display while the vehicle is also moving up and down or angularly.

Lackner, J. R., & Dizio, P. (1974). Altered sensory-motor control of the head as an etiological factor in space-motion sickness. *Human Factors,* no. 68, 784–786.

Results indicate that space-motion sickness is the result not just of unusual patterns of vestibular activation and processing, but also of altered sensorimotor control head torque.

Lintern, G. (1990). The learning strategies program: Concluding remarks. ARI Research Note 90-46 (AD-A226 016), p. 21. U.S. Army Research Institute for the Behavioral and Social Sciences, Alexandria, VA, July.

Lintern, G., Thomley, K. E., Nelson, B. E., & Roscoe, S. N. (1984). Content, variety, and augmentation of simulated visual scenes for teaching air-to-ground attack. (AD-A145 218), p. 74. Naval Training Equipment Center, Orlando, FL, July.

This paper compares the transference of skills and the quality of training for experienced and inexperienced pilots. The researchers found no evidence that pilots with no experience in air-to-ground attack should be treated differently from experienced pilots.

Lintern, G., Roscoe, S. N., Koonce, J. M., & Segal, L. D. (1990a). Transfer of landing skills in beginning flight training. *Human Factors, 32*(3), 319–327.

Experimental students required significantly fewer pre-solo landings in the airplane than did the paired controls, representing a potential saving of 1.5 pre-solo flight hours per student.

Lintern, G., Roscoe, S. N., & Sivier, J. E. (1990b). Display principles, control dynamics, and environmental factors in pilot training and transfer. (AD-A229 283), pp. 299–317.

Magee, L. E., Kantor, L., & Sweeney, D. M. C. (1987). Simulator induced sickness among Hecules aircrew. *AGARD Conference Proceedings No. 433 Motion Cues in Flight Simulation and Simulator Induced Sickness.* Advisory Group for Aerospace Research and Development (AGARD), Neuilly Sur Seine, France, September–October.
Eighty-three percent reported symptoms of simulator sickness. The researchers found no evidence to indicate that pilot experience influenced susceptibility to simulator sickness.

Martin, E. L., & Waag, W. L. (1978). Contributions of platform motion to simulator training effectiveness: Study I—basic contact. (AD-A058 416), p. 40. Air Force Human Resource Laboratory, Williams AFB, TX, June.
A comparison of the effectiveness of motion and no-motion simulators.

Martin, E. A. (1992). *Motion and Force Simulation Systems, I.* Flight Simulation Update—1992, SUNY Binghampton–Watson School of Engineering, Binghampton, NY, January (6–10).
Discussion of perception as related to application in motion systems. Also discusses motion simulator washout.

McCauley, M. E., & Kennedy, R. S. (1976). Recommended human exposure limits for very low-frequency vibration. TP-76-36 (AD-B015 449), p. 26. Pacific Missile Test Center, Point Mugu, CA, 29 September.

McMillan, G. R. (1992). *Cue Integration and Synchronization.* Flight Simulation Update—1992, SUNY Binghampton–Watson School of Engineering, Binghampton, NY, January (6–10).
Discusses the issues of cue integration and synchronization in terms of their effects on human sensation, perception, and performance. Includes an informative discussion of the motion and depth cues that should and should not be included in a simulator. Also included are discussions of training effectiveness, performance, and transfer of training research, and an introduction to simulator sickness and the theory. Includes an excellent explanation of the Riccio/Stoffregen theory.

Money, K. E., Cheung, B. S., & Kirienko, N. M. (1987). An illusion of reversed direction in hyperopes. *Perceptual and Motor Skills,* no. 65, 615–618.

Orlansky, J., & String, J. (1977). Cost-effectiveness of flight simulators for military training: Volume I—Use and effectiveness of flight simulators. (AD-A052 801), pp. 97–109. Office of the Secretary of Defense, Alexandria, VA, August.
The seminal paper regarding cost-effectiveness for flight simulators.

Orlansky, J., & String, J. (1979). The cost-effectiveness of military training. (AD-P000 168), pp. 97–109. Office of the Secretary of Defense, Alexandria, VA.
A cost–benefit analysis of flight simulators.

Owen, D. H., Wolpert, L., Hettinger, L. J., & Warren, R. (1984). Global optical metrics for self-motion perception. *The IMAGE III Conference Proceedings,* pp. 406–415. Air Force Human Resources Lab, Williams AFB, TX, Phoenix, AZ, 30 May–1 June.
The researchers explore the effect of varying the uniformity ground texture on a pilot's ability to estimate ground speed. Interestingly, this report discards the ecological approach of Stoffregen and Riccio.

Parrish, R. V., & Williams, S. P. (1990). Stereopsis cueing effects for hover-in-turbulence performance in a simulated rotorcraft. NASA TP-2980/AVSCOM TR-90-B-002 (AD-A224 484), p. 59. U.S. Army Aviation Systems Command, Hampton, VA, May.
The purpose of the effort here was to quantitatively determine the efficacy of stereopsis cuing in enhancing the situational awareness of pilots conducting precision tasks. The objective and subjective results of this experiment indicate that stereopsis cuing is an effective way to enhance situational awareness of pilots using pictorial displays.

Pfeiffer, M. G., & Scott, P. G. (1985). Experimental and analytic evaluation of the effects of visual and motion simulation in SH-3 helicopter training. 85-002 (AD-B101 324), p. 62. Naval Training Systems Center, Orlando, FL, December.

Pfeiffer, M. G., & Horey, J. D. (1987). Training effectiveness of aviation motion simulation: A review and analysis of the literature. Special Report 87-007 (AD-B120 134), p. 41. Naval Training Systems Center, Orlando, FL, December.
Literature review of 45 transfer of training studies.

Previc, F. H. (1989). Towards a physiologically based HUD symbology. USAFSAM-TR-88-25 (AD-A207 748), p. 19. USAF School of Aerospace Medicine, Brooks AFB, TX, January.

Prophet, W. W. (1974). Simulation and aircrew training and performance. HumRRO-PP-4-74 (AD-780 688), p. 15. Human Resource Organization, Washington, D.C., April.
This paper outlines some major areas of use of simulation in Army aviation and comments on current research.

Sekular, R., Tynan, P. D., & Kennedy, R. S. (1981). Sourcebook of temporal factors affecting information transfer from visual displays. (AD-A109 907), p. 177. U.S. Army Research Institute for the Behavioral and Social Sciences, Alexandria, VA, 1 June.
This report collects in one document the important research literature on temporal factors in vision. The subject matter is perception of temporal events—specifically motion perception. Chapters on illusion of motion, motion perception in the periphery, flash sensitivity, and flicker sensitivity.

Self, H. C. (1986). Optical tolerances for alignment and image differences for binocular helmet-mounted displays. AAMRL-TR-86-019 (AD-A174 536), p. 39. Armstrong Aerospace Medical Research Laboratory, Wright Patterson AFB, OH, May.
Review of the literature on optical alignment and image difference tolerances for binocular devices. Tolerances for vertical and horizontal misalignment and for rotation, magnification, and luminance differences are recommended.

Sheppard, D. J., Hettinger, L. J., Westra, D. P., & Jones, S. A. (1987). Simulator evaluation of lineup visual landing aids for night carrier landing. EOTR-88-1 (AD-A191 212), p. 56. Naval Air Systems Command, Orlando, FL, 10 March.

Stark, E. A. (1992). *Training and Human Factors in Flight Simulation.* Flight Simulation Update—1992, SUNY Binghampton–Watson School of Engineering, Binghampton, NY, January (6–10).
Author discusses perception and learning, transfer of training, and gives references to papers that have done these studies. Stark then talks about motion perception and learning. Includes discussion on visual simulation and visual image generation.

Stern, J. A., & Goldstein, R. (1988). An evaluation of electrooculographic, head movement and steady state evoked response. AAMRL-TR-88-036 (AD-A236 505), p. 127. Washington University Behavior Research Laboratory, St. Louis, MO, July.
The focus of this paper is on the effect of a lightweight helmet-mounted display (HMD) system had on strategies of visual information intake.

Stewart, R. (1985a). Psychology of spaceflight: Suggested bases of space motion sickness: Perceptual disorientation and elevated stomach pH. *Perceptual and Motor Skills,* no. 60, 189–190.

Stewart, R. (1985b). Space flight: Isolation of perceptual variable in parabola flight sickness with countermeasure to lower gastric pH. *Perceptual and Motor Skills,* no. 60, 960–962.

Stewart, R. (1985c). Space flight: Variables of motion sickness. *Perceptual and Motor Skills,* no. 61, 397–398.
Author discusses pH level in stomach along with prostaglandins and disorientation from motion variables.

Stinnett, T. (1984). Sensor-coupled vision systems. (AD-B159 536), p. 29. Westinghouse Defense and Electronics Center, Baltimore, MD.
This experiment evaluated various FOVs and their respective performance along with the requirement cases of the head restrained and unrestrained. Discussion on the "bright eye concept."

Stoffregen, T. A., & Riccio, G. E. (1988). An ecological theory of orientation and the vestibular system. *Psychological Review,* no. 95, 3–14.
Theory against a fundamental assumption of traditional theories of orientation. There are two important areas of disagreement with the classical approach to spatial orientation. One is the nature of information for orientation; the other concerns cooperation between perception and control of orientation.

Trautman, E., Ellingstad, V., Lilienthal, M., & Trautman, M. A. (1988). Quasimonochromatic environments and the resting point of accommodation. NTSC TR 88-028 (AD-A205 938), p. 66. Naval Training Systems Center, Orlando, FL. This investigation explored the importance of color as a factor in deterioration of correct visual accommodation and involuntary regression to the resting point of accommodation.

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 86-D-0026-1 (AD-A180 196), p. 74. Naval Air Systems Command, Washington, D.C., 26 December.
Simulator performance was differentially affected by lag with the longest lag producing the worst performance. Of further concern, lag had no effect on any of the sickness ratings.

Umeda, A. Y., Martin, S. W., & Merrit, J. O. (1991). Remote vision systems for teleoperated ground vehicles. (AD-A236 765). Naval Ocean Systems Center, San Diego, CA, May.
Another study referencing FOV and stereoscopic vision advantages.

Van Cott, H. (1990). Lessons from simulator sickness studies. *Motion Sickness, Visual Displays, and Armored Vehicle Design,* pp. 76–84. Ballistic Research Laboratory, APG, MD, Washington, DC, April.

Waag, W. L. (1981). Training effectiveness of visual and motion simulation. AFHRL-TR-79-72 (AD A094 530), p. 30. Operations Training Division—HRL, WAFB, Williams AFB, AZ, January.

A review of the literature concerning the training effectiveness of visual motion simulation is presented in this report.

Webster, J. A. (1988). Stereoscopic full field of vision video system for use in real time visual telemetry. DI-S-4057 (AD-B121 941), p. 43. DARPA, Arlington, VA, April 27.

This paper discusses field-of-view, update rates, and HMDs.

Wells, M. J., & Griffin, M. J. (1987). A review and investigation of aiming and tracking performance with head-mounted sights. *IEEE Transactions on System, Man and Cybernetics,* no. SMC-17, No. 2, 210–221, March/April.

Westra, D. P. (1983). Simulation training for aircraft carrier landings. (AD-P000 204), pp. 397–404. Canyon Research Group, Orlando, FL.

Results showed that the simulator and training factors generally produced either small differences or no differences at all in transfer effectiveness.

Westra, D. P., & Lintern, G. (1985). Simulator design features for helicopter landing on small ships. NAVTRASYSCEN 81-C-0105-13 (AD-A169 514), p. 69. Naval Training Systems Center, Washington, D.C., 27 September.

VTRS—studied the effects of six simulator features on performance, including field of view and visual lag.

Westra, D. P., Lintern, G., Sheppard, D. J., Thomley, K. E., Mauk, R., Wightman, D. C., & Chambers, W. S. (1986). Simulator design and instrumental features for helicopter shipboard landings. NAVTRASYSCEN 85-C-0044-2 (AD-A203 992), p. 86. Naval Air Systems Command, Washington, D.C., 18 June.

This paper is largely concerned with the transference of skill from simulator to real aircraft.

Westra, D. P., Sheppard, D. J., Jones, S. A., & Hettinger, L. J. (1987). Simulator design features for helicopter shipboard landings. TR-87-041 (AD-A203 992), p. 61. Naval Training Systems Center, Orlando, FL, July.

Young, L. R. (1971). Developments in modelling visual-vestibular interactions. AMRL-TR-71-14 (AD 737 795), p. 94. Whittaker Corporation, Waltham, MA, January.

This is a detailed report on ocular issues.