Cybersickness: Perception of Self-Motion in Virtual Environment.

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Abstract

Human perceptual systems have evolved to provide accurate information about orientation and movement through the environment. However, these systems have been challenged in the past century by modern transportation devices and will be further challenged by virtual environments (VEs) and teleoperator systems. Illusory self-motion within a VE ("cyberspace") will be entertaining and instructive, but for many users it will result in motion sickness ("cybersickness"). Sensory conflict theory and the poison hypothesis provide an unproven theoretical foundation for understanding the phenomenon. Although no single engineering solution is likely, the problem can be contained by a combination of engineering design, equipment calibration, and exposure management.

1 Motion Sickness

Motion sickness is characterized by a diverse set of symptoms but is primarily exemplified by nausea and vomiting (emesis). A variety of species, including chimpanzees, monkeys, horses, cows, birds, and fish exhibit motion sickness (Money, 1970, 1990). The vestibular system (see Howard, 1986a) is fundamental and essential for motion sickness. Only people with a nonfunctional vestibular system are totally immune to motion sickness (James, 1882; Kennedy, Graybiel, McDonough, & Beckwith, 1968). Symptoms of motion sickness are common in some proportion of the population under a variety of conditions usually involving a sustained exposure to periodic motion (Guignard & McCauley, 1990; Reason & Brand, 1975). In the past, it has been most commonly associated with man-made forms of transportation and given the corresponding name such as sea sickness, air sickness, car sickness, and space sickness.

The exact causes of motion sickness are not thoroughly understood. Crampton (1990) has compiled a recent review of the topic. Sensory conflict theory (Reason & Brand, 1975) has served to consolidate much of the thinking about this malady, but it has been criticized for succeeding more in post-hoc explanation than in predictive power. Both actual motion and visually implied motion, as in VE travel, stimulate electrical activity in the vestibular nuclei (Brizzee, 1990; Waespe & Henn, 1977). Therefore, it should be no surprise that both actual and virtual motion are capable of inducing motion sickness. Wide-field-of-view displays with rich scene content and good resolution can be compelling and may induce a strong sense of self-motion, called vection. Vection may contribute to "presence" in VE systems and there is evidence that vection is necessary to induce simulator sickness (Hettinger, Berbaum, Kennedy, Dunlap, & Nolan, 1990; Kennedy, Hettinger, & Lilienthal, 1990).

The measurement of motion sickness is challenging because (1) there are a variety of symptoms, (2) symptomatology is internal, nonobservable, and subjective, (3) there are large individual differences in both symptom profiles and general susceptibility, and (4) the constellation of symptoms develops over time periods ranging from a few minutes to several hours. Physiological indices of motion sickness have met with some success, although symptom profiles have been idiosyncratic (Cowings, Suter, Toscano, Kamiya, & Naifeh, 1986; Miller, Sharkey, Graham, & McCauley, 1993; Stern, Koch, Stewart, & Lindblad, 1987). Harm (1990) has recently reviewed the physiology of motion sickness symptoms and confirmed the variety and complexity of individual responses to real or apparent motion stimuli.

What survival value is achieved by species who empty the contents of their stomachs in response to real or vir-

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tual periodic accelerations (Money, 1990)? Triesman (1977) suggested that animals who ingested poisons suffered physiological disturbances involving the coordination of sensory inputs from vision, the vestibular system, and other proprioceptors controlling limb movements and eye movements. This disruption served as an early warning system for detecting neurotoxins and survival was enhanced by eliminating the stomach contents through vomiting. Money and his colleagues have reported research results that support this "poison hypothesis" (Money, 1990; Money & Cheung, 1983).

2 Perceptual–Motor Control of Self-Motion

Humans normally accomplish with aplomb the seemingly mundane task of remaining upright and moving through their environment. Closer analysis reveals this to be a very complex process. The skeletal and neuromuscular infrastructure must be intact and a hierarchy of perceptual–motor feedback loops must function in concert (Howard, 1986a). Information supporting postural control and locomotion is provided by visual, vestibular, auditory, and proprioceptive senses. Vestibular signals and peripheral vision seem to be particularly important for spatial orientation and the detection of self-motion. The interaction among visual, vestibular, and proprioceptive information helps to resolve ambiguities about orientation and self-motion relative to the movement of objects in the environment (Howard, 1986b). Such ambiguities may be created by VEs and teleoperator systems because they provide visual, but not vestibular, information consistent with self-motion.

Perceptual and perceptual–motor systems are modifiable, enabling us to accommodate, adapt, acclimatize, and learn to function adequately under changing conditions (Welch 1978, 1986). The plasticity of our perceptual–motor systems enables successful locomotion and manipulation of objects during periods of body growth (for the first two decades or so), physical decline in later years, and fluctuations in weight and strength throughout our lifetimes. Similarly, this plasticity enables us to compensate for changes in environmental conditions or transformations in the optical array induced by man-made devices such as eye glasses, vehicle windscreens, and the visual display systems found in simulators, teleoperator systems, or VEs.

A transformed environment causes errors in perception and perceptual–motor control that can initiate both adaptation and motion sickness. One conception is that those individuals who adapt quickly may successfully avoid sickness; those who adapt slowly may become sick before achieving adaptation. The adaptive process has a cost, however, that can be characterized in terms of several categories—time, level of performance, and attention (i.e., application of cognitive resources required). Adaptation to a transformed world does not happen immediately. Rather, it occurs over time ranging from less than a second to weeks or months, depending on the transformation and the type of adaptation (Welch, 1986). During the period of incomplete adaptation to a transformed world, the individual may exhibit errors in performance reflecting inaccurate perception of space or time. These performance problems may be exemplified as errors in reaching, eye movement (see Ebenholtz, 1988 and this volume), or vehicular control. With minor transformations, performance may be maintained at a satisfactory level by allocating more attention to a normally routine task. Larger transformations and longer exposure times to VEs will result in an increasing incidence of motion sickness and will require longer adaptation periods.

3 Sources of Transformation in VEs

There are several potential sources of transformation in VEs including optical distortions, temporal distortions, and the alteration of the normal correspondence between visual and vestibular information about spatial dynamics. Teleoperator systems are functionally equivalent to VEs in that they both involve user control of movement through an environment that is synthetic or remote, respectively. Both teleoperator and VE systems violate the normal correspondence between visual and vestibular patterns of sensation regarding self-motion.

Teleoperator and VE systems have a vast number of potential applications. For instructive purposes, we will create an arbitrary distinction between "near" and "far" applications and suggest that cybersickness will occur primarily in "far" applications. Near applications involve proximate objects, stationary self, and the absence of vection. Examples include virtual representations of medical procedures, automotive procedures, and cockpit anthropometry. Vestibular function in near applications is primarily limited to head movements and does not involve whole-body rotations or linear accelerations.

By contrast, far applications involve distant objects, i.e., terrain, self-motion (travel) through the environment, and the illusion of self-motion (vection). Examples include control of a moving teleoperator sensor platform or "cybertravel" through any real or imagined terrain. Size and speed distortions are part of the power of the VE medium (i.e., touring the Milky Way or a DNA molecule). Vestibular function in far applications usually involves a violation of the normal stimulation patterns. The motion implied by the visual display system is not corroborated by the vestibular input. The vestibular signal usually is null (i.e., a seated 1-G environment). Some types of VE, such as flight simulators, have attempted to provide input to the vestibular and proprioceptive senses via motion-base systems.

As a matter of definition, we consider flight simulators and driving simulators to be particular "far" applications within the larger domain called VE. It follows that simulator sickness is a subset of the motion sickness experienced from travel through VEs, for which we suggest the more general term "cybersickness."

4 Undesirable Side Effects

We believe that motion sickness is not only predictable but inevitable in a substantial proportion of users in "far" applications of VEs. "Near" applications are not expected to generate motion sickness unless frequent head movements are required and some aspect of the VE has caused a transformation in the vestibular ocular response (see Ebenholtz, this issue).

Motion sickness can be considered an unwanted side effect of traveling through VEs. However, not all users will suffer from it because there are large individual differences in susceptibility. Less common consequences include postexposure deterioration of postural stability, dizziness, and false sensations of movement or rotation. These effects have been reported in the literature on simulator sickness (Kennedy, Lilienthal, Berbaum, Baltzley, & McCauley, 1989).

Dizziness, disorientation, and decrements in postural stability are worrisome because of the implications for the safety and health of the user. These issues have been raised in the simulation domain, but they are also applicable to the larger domain of VE. After prolonged or intense exposure to a VE system, the user may be at risk when engaging in certain types of activities such as automobile driving. It is immediately apparent that episodes of dizziness and disorientation while driving could be problematic. We are not yet aware of any litigation involving disorientation of a VE user, but such a development would not be surprising.

In practice, out of concern for both the potential liability and for the welfare of the individuals who participate in the experiments, we have not allowed pilots who develop simulator sickness in our research program to drive automobiles or fly aircraft for several hours following their simulated flight. Both the Navy and the Army have had local policies that prohibit pilots from flying an aircraft for a number of hours after exposure to a simulator (Crowley, 1987).

5 The Expected Incidence of Cybersickness

Pilots tend to be less susceptible to motion sickness than the general population. They are "self-selected" and subject to attrition based on their resistance to motion sickness. VEs will not benefit from this selection process because they will be aimed at a broader proportion of the population than are flight simulators. Consequently, users of VE systems are likely to be more susceptible to motion sickness. The implication is that cybersickness may be more common than simulator sickness, which typically ranges from 20 to 40% in military pilots

(Kennedy et al., 1989). In one study of teleoperator land vehicles, five of eight drivers reported symptoms of motion sickness either while controlling the vehicle or immediately after (Pepper, 1986).

The frequency of cybersickness in commercial VE systems could be exacerbated by poor calibration practices. The proper operation of commercial and military flight simulators is normally verified on a regular basis or whenever anomalies are observed. It is likely that this level of calibration will not be maintained on commercial VE systems. Failure to maintain calibration of the devices will result in increased spatial and temporal distortions.

The physical and psychological state of the users of commercial VE systems also will be more varied than is typical of users of flight simulators. For example, it is more likely that some of the users of commercial VE systems will be under the influence of medications or alcohol. Kruk (1992) has suggested that medication increases the susceptibility to simulator sickness in a research simulator. Anecdotal evidence from driving simulators also suggests that older drivers are particularly susceptible to sickness. The combined impact of these factors is likely to be a higher incidence of cybersickness than the known incidence of simulator sickness.

6 Engineering Features

The search for an engineering solution to simulator sickness has not met with success and may be equivalent to the search for the grail. Even the most capable flight simulators produce some level of sickness, given that they have a wide-field-of-view visual system (Kennedy et al., 1989).

6.1 Motion-Base Systems

Current teleoperator and virtual reality systems typically have no motion-base system. A clear discrepancy is created between the self-motion implied by the visual display system and the lack of corresponding stimulation of vestibular and proprioceptive senses. Therefore, even excellent visual display systems with no spatial–temporal distortion may induce motion sickness because corroborating vestibular and proprioceptive feedback is lacking. The claim that improved visual systems will solve the problem is simply false. A theoretically perfect visual display system would still provide information about self-motion that conflicts with the (lack of) vestibular stimulation. Regardless of the excellence of the visual display system, the patterns of corroborating visual and vestibular information that have been strengthened through years of experience are violated in a VE system when vestibular stimulation is absent. Therefore, the motion-base solution appears, at first glance, to be a reasonable approach.

Information about the effectiveness of motion bases in flight simulation may be instructive. Flight simulation is a particular instance of a VE. In particular, advanced simulators utilizing a head-tracked, wide-field-of-view display are functionally equivalent to the usual conception of a VE display system. We believe that flight simulation can be considered a model for self-motion issues that will be encountered in future VEs. For example, simulator sickness has been found to occur in a wide variety of flight simulators, with and without motion bases (Casali, 1986; Kennedy et al., 1989; McCauley, 1984). Motion bases are included in the design of many flight simulators, usually because someone in charge of the design requirements believes that they (1) enhance training effectiveness, (2) reduce simulator sickness, or (3) are desired by the user community. Because the designers of future VE systems are likely to entertain similar thoughts, the evidence supporting these beliefs deserves some examination.

The effectiveness of motion cues for transfer of training has been debated for some time. This is not the forum for a review of that debate. But there is little evidence to support the claim that existing motion-base platforms enhance transfer of training (Martin, 1981; McDaniel, Scott, & Browning, 1983). Flight students obtain training benefit from their simulator exposure whether or not a motion platform is included. Manual control performance in the simulator, on the other hand, has been shown to be enhanced by platform motion for some flight tasks (Ricard & Parrish, 1984).

One hypothesis consistent with sensory conflict theory is that a motion base will decrease the conflict inherent between visually implied motion and the null signal (1-G), which is provided to the vestibular system in a fixed-base simulator. However, a study that we recently completed in the NASA-Ames Research Center's Vertical Motion Simulator (VMS), the world's largest motion-base simulator, fails to support that hypothesis (Sharkey & McCauley, 1992). In that experiment, specific helicopter flight tasks were used because (1) they caused severe motion sickness in all seven pilots who performed them previously in a fixed-base, wide-field-of-view simulator, and (2) they entailed relatively low-amplitude motion maneuvers, ones that could be well represented in the large VMS motion base. Counter to our expectations, the pilots experienced just as much motion sickness in the motion-base condition as in the fixed-base condition.

The adequacy of the motion provided by a motion base can be assessed only with respect to the flight tasks. The more aggressive the maneuvers, the greater the discrepancy between the dynamics of the actual aircraft and the simulator, while the visual flow remains the same in the aircraft and the simulator. That is, the fidelity of the visual dynamics is not a function of maneuvering intensity but a motion-base platform suffers an increasing loss in fidelity as vehicle maneuvering increases. As an extreme example at the low end, a motion base is irrelevant because it is quiescent when flying straight and level in smooth air. At the other extreme, motion bases may be completely inadequate when applied to a combat maneuvering scenario entailing rapid, multiple, and sustained accelerations. No motion base is capable of providing more than the initial onset of a large, sustained acceleration without leaving the building.

The hydraulic, hexapod motion bases typically found on flight simulators are constrained to approximately $\pm 35°$ angular displacement, ± 2 m linear displacement, and a bandwidth of up to 4 Hz. Such limited travel is adequate only for very gentle maneuvering, perhaps like that experienced in routine operation of commercial airlines, where reports of simulator sickness are rare. For more aggressive maneuvering, "washout" algorithms are implemented to keep the platform within its physical limits. Washout algorithms reduce the gain and the duration of the platform accelerations relative to the actual vehicle. Initial onset cues are followed with subthreshold accelerations in the opposite direction to keep the simulator within the constraints of its physical envelope. Thus the washout itself may sometimes contribute to a problem of sensory conflict by producing suprathreshold accelerations in the wrong direction.

Although the evidence does not support claims that a motion base is an engineering solution to the sickness problem, it is possible that less expensive alternatives, such as a vibration seat, would provide "noise" to the vestibular and proprioception senses thereby reducing the conflict with the visually implied motion.

6.2 Calibration and Other Engineering Issues

While excellent engineering may not prevent sickness, poor engineering or calibration certainly can contribute to it. Proper calibration of alignment, size, and focus of optical displays are important in the management of sickness. Transport delays, uncalibrated visual displays, and inaccurate head tracking, among other features, have been suggested to exacerbate simulator sickness. It is likely that other applications of VEs also would suffer from imprecise engineering. Inaccuracy, variability, or lags in head tracking may be of particular relevance to VE systems for which a head-tracked display is generally considered essential.

Other often-mentioned engineering approaches to managing sickness include (1) minimizing the delay between visually and physically signaled acceleration cues, and (2) minimizing the time between the acceleration cue onsets in the VE and the cue onsets that would occur in the real vehicle. Such lags may contribute to a high occurrence of illness, but it is likely that with regard to fixing these problems, we are already in the region of diminishing returns. That is, further reductions are increasingly difficult and expensive, and have less and less effect on the incidence of sickness.

7 Exposure Management Practices

The following lessons learned in conducting research on sickness in flight simulators are likely, in our opinion, to be applicable to other forms of VEs. Suggestions for managing the problem are in italics.

As the exposure time to a VE increases from minutes to several hours, the probability of developing undesirable symptoms increases. Adaptation can be promoted by repeatedly exposing the individual to the altered environment, using exposure durations that are brief enough to avoid the onset of adverse symptoms. *Exposure time should be limited until adaptation to the VE has occurred.*

The data relating the maneuvering intensity and sickness are not completely consistent. Sharkey and McCauley (1991) did not find that increased maneuvering intensity led to reliably greater illness. However, the difference between the two maneuvering intensity conditions was not great. On the other hand, McCauley, Hettinger, Sharkey, and Sinacori (1990) found some evidence suggesting that increased maneuvering intensity did lead to increased sickness, although it must be noted that maneuvering intensity and exposure duration were knowingly confounded in this study, and so the issue remains unresolved. From a theoretical perspective, the aggressiveness of the maneuvers performed is related to the magnitude of the intersensory conflict in a vehicle simulator. Increased maneuvering aggressiveness would be expected to result in increased incidence of sickness. Therefore, *tasks that require high rates of linear or rotational acceleration should be avoided, or kept brief, until the individual has fully adapted to the altered environment.*

Individual differences in susceptibility to simulator sickness are large, ranging from virtually immune to extraordinarily sensitive. As mentioned earlier, we expect that the range of sensitivity may be larger in the general population than among pilots. Attempts to design a single adaptation program for all potential users almost certainly will fail. Nearly immune users will need no adaptation period while others may require a lengthy, incremental process. *Users of VEs should be considered on an individual basis when determining an adaptation program.*

The rate at which objects flow through the visual scene, specifically the rate of global visual flow (GVF), has been shown to be related to sickness (Sharkey & McCauley, 1991). GVF is simply the observer's velocity divided by the observer's eye height above the terrain surface (Owen, 1990). To minimize the sickness problem, *self-movement through a VE should be at high altitudes above the terrain and/or at lower speeds.*

In aircraft simulators, freezing the simulation abruptly or freezing the simulation with the vehicle at an unusual pitch or roll attitude seems to promote sickness. Similarly, performing extraordinary maneuvers, such as "flying" backward to reposition the aircraft, tends to be unsettling. Therefore, *unusual and extraordinary maneuvers such as these should be avoided in VEs.*

Medication intended to prevent motion sickness may prove useful for some people, but side effects such as dry mouth and drowsiness are common. We are not aware of any research conducted to date on the application of anti-motion sickness medication for the prevention of cybersickness. On the other hand, the use of alcohol, drugs, or medication may exacerbate the problem. *Users of VE systems should be informed about the potential negative interactions between the ingestion of pharmacological agents and "cybertravel" through a VE.*

In general, *users of VE systems should be informed of the possible adverse effects including motion sickness, perceptual aftereffects, decreased postural stability, and, in rare cases, delayed onset of symptoms.*

Finally, *users should be advised to allow for recovery time after cybertravel before actively engaging in potentially dangerous activities in the real world, such as driving an automobile.*

VEs represent a powerful tool for expanding the scope of our experience. Knowledge about cybersickness will help manage the scope of this side effect and enable the benefits of the new technology to be enjoyed more fully.

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