Configural Scoring of Simulator Sickness, Cybersickness and Space Adaptation Syndrome: Similarities and Differences?

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ABSTRACT

From a survey of ten U.S. Navy flight simulators a large number (N > 1,600 exposures) of self-reports of motion sickness symptomatology were obtained. Using these data, scoring algorithms were derived, which permit examination of groups of individuals that can be scored either for 1) their total sickness experience in a particular device; or, 2) according to three separable symptom clusters which emerged from a Factor Analysis. Scores from this total score are found to be proportional to other global motion sickness symptom checklist scores (e.g., Lackner & Graybiel, 1984) with which they correlate (r = 0.82). The factors that surfaced from the analysis include clusters of symptoms referable as **nausea, oculomotor disturbances, and disorientation (N, O, and D).** The factor scores may have utility in differentiating the source of symptoms in different devices. The present chapter describes our experience with the use of both of these types of scores and illustrates their use with examples from flight simulators, space sickness and virtual environments.

Key Words:
cybersickness, space sickness, simulator sickness, virtual environment, virtual reality, aftereffects

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INTRODUCTION

Signs and Symptoms

Written reports about conditions which are conducive to causing **motion sickness** date back at least to Hippocrates. From the standpoint of operational efficiency, Julius Caesar, Lawrence of Arabia, and Admiral Nelson were all plagued with bouts of sickness (Money, 1972), but these individuals appear to have either adapted over exposures or otherwise coped with the environments and were thereby able to distinguish themselves in these environments. However, the practical rule is that motion sickness can be expected to adversely affect operational efficiency (Benson, 1978), and the U.S. Navy has long been concerned with the influence of various ship motions on seasickness and seakeeping performance. Ernie Pyle, who witnessed first-hand, the World War II D-Day invasion in Normandy, wrote about what he observed to be the enormously reduced fighting efficiency of soldiers and sailors due to sea sickness and seasickness drugs, and it was observed that the landing occasioned "...the greatest mass vomiting ever known in the history of mankind..." (p. 18, Reason & Brand, 1975). If reports of virtual environment (VE) sickness continue unabated (Kolasinski, 1995; Johnson, 1997), and if the recent projected estimates of increased device usage are correct, particularly for entertainment and education (Machover, 1996), VE sickness may soon surpass earlier estimates.

Symptoms of motion sickness have been with us since the means of passive conveyance achieved wide use. The pathognomonic sign is vomiting (and at times, retching). The other signs of the disease are many and disparate. They include overt manifestations such as pallor, sweating, and salivation (Colehour & Graybiel, 1966; Stern, Koch, Stewart, & Lindblad, 1987), and curiously, lassitude and a reluctance to communicate. The major reported symptoms of motion sickness imply involvement of the vagus nerve complex related to the autonomic nervous system, and these include nausea, drowsiness, general discomfort, apathy, headache, stomach awareness, disorientation, fatigue, and incapacitation (Kennedy & Frank, 1986). Accompaniments, but less well-known as outcomes, are postural and eye/hand incoordinations (Kennedy, Stanney, Compton, Drexler, & Jones, 1999) and the sopite syndrome (Graybiel & Knepton, 1976). The latter problems may occur as the sole manifestation of sickness or may be present when other combinations of symptoms are present, and for this reason are insidious and portend a condition that could lead to accidents following exposures. Additional signs of motion sickness include changes in cardiovascular, respiratory, gastrointestinal, biochemical, and temperature regulation functions.

In addition to humans, most animals (monkeys, dogs, birds) appear to exhibit traditional signs of motion sickness (viz., vomit, salivation, drowsiness). Further, fish and seals being transported in trucks and aboard ships have been known to regurgitate their food (Chinn & Smith, 1955); and even rats - which do not have a vomiting mechanism - show a disordered operant response (Eskin & Riccio, 1966) after protracted rotation.

Genesis

Nausea, admittedly the cardinal symptom of sea-sickness, has its origins in the Greek word for sailor ***[nautes]*** or boat ***[naus].*** Symptoms at sea, likely the most prevalent form of sickness, appear to occur when the predominant motions of the environment are within the frequency range centered around 0.2 Hz (McCauley & Kennedy, 1976), and the amount of acceleration and time spent at that frequency (versus one higher ***or*** lower) is a major determinant of sickness incidence and severity. Thus, vehicles that move in the low frequency range (viz., most seagoing vessels, some cars, some all-terrain-vehicles, large surface effect ships, most high winged aircraft, ferries [with or without stabilization gear], buses,

swings, some moving base simulators, perhaps MAGLEV, camels) also exhibit their share of sickness. While it is attractive to posit that most forms of motion sickness can be avoided if one were to design vehicles to only move either below 0.01 Hz ***or*** above 0.80 Hz (cf., MILSTD 1472C, 1981), there are other forms of motion sickness where the presence of a stimulus within the bandwidth around 0.2 Hz stimulus is not so obvious. Specifically: 1) rotation induced sickness (e.g., carnival devices, merry-go-rounds), particularly those involving Coriolis-type stimulations (Kennedy & Graybiel, 1965), which increases as velocity increases; 2) space sickness, which seems to be related to activity levels during early microgravity exposures and aftereffects, which appear to be proportional to the duration of exposure, but there is currently no satisfactory way to predict who is prone or what the physical stimulus is that causes it (retinal slip, vestibulo ocular reflex recalibration, otolith tilt reinterpretation hypothesis, stomach contents at microgravity, etc.) (cf., Reschke, Kornilova, Harm, Bloomberg, & Paloski, 1997 for a very complete review); and 3) many environments where dynamic and static visual displays have been shown to induce motion sickness (Hettinger & Riccio, 1992), for example Witkin (1949) produced unwanted motion sickness using only a tilted chair; and relatedly, 4) dynamic visual scenes where depth coding is disrupted.

Visually induced motion sickness (VIMS)

While the statement may appear to be axiomatic, it is not entirely true that motion sickness only occurs when the physical environment moves. For example, visually perceived movement can influence the motion sickness experience. Erasmus Darwin (1794) in his "Zoonomia" related that his grandson, who suffered greatly from the motions of the ship "Beagle," expressed the view that it was visual disturbances which constituted the principal cause of seasickness, and while blind people can become seasick, "...people can increase their resistance to motion sickness by being blindfolded in otherwise provocative moving environments..." (Kennedy, Tolhurst, & Graybiel, 1965).

Around the turn of the century Stratton (1897), viewing real images through inverting prisms, described dizziness and nausea in individuals who were made to walk while wearing these glasses. Because most investigators found that humans can rapidly adapt to these unusual conditions, they subsequently became a popular paradigm for the study of central nervous system plasticity and a very large research literature and much theory on perceptual adaptation emerged from this work carrying down into the 50s and 60s (Kohler, 1968).

Also around the turn of the century, Wood (1895) described the Haunted Swing Illusion from the San Francisco World's Fair. This device offered the first example of which we are aware of a purely visual stimulus producing sickness and disorientation. In 1949, Tyler and Bard alluded to others who had made similar observations regarding the importance of visual factors in motion sickness, but they questioned whether these visually-related problems were etiologically identical to those of motion sickness. Crampton and Young (1953) began to explore motion sickness and the perception of ego- or self-motion, and their work, plus the work of clinical otolaryngologists with optokinetic stimuli, anticipated the research concerned with the perception of illusory self motion (Dichgans & Brandt, 1978).

Dichgans and Brandt (e.g., 1972, 1973, 1978) explored systematically how visual stimulation can influence the perception of self-motion (called "vection"). Their work on vection forms the basis of what is now known about the psychophysical determinants of the perception of ego-motion and along with Howard and Howard (1994) and Kennedy, Hettinger, Harm, Ordy, and Dunlap (1996), are sources that can be consulted for psychophysical parameters that govern the experience of vection. It has been argued that the perception of immersion and presence from flight and auto simulators is related to the vection experience (Hettinger, Berbaum, Kennedy, Dunlap, & Nolan, 1990)

In many of the situations in flight simulators where visually induced motion sickness (VIMS) occur, it appears that similar symptoms of motion sickness are present (Hettinger & Riccio, 1992). Importantly, the clusters of symptoms encountered when vection is experienced are also like those that have been reported in simulators and some VEs appear to exhibit different symptoms from seasickness profiles. But the relationship of vection to sickness and presence is not simple since it must reconcile the following facts. For example, it is known that vection is an important ingredient in visually induced sickness because persons who do not ordinarily get vection also do not become sick (Hettinger, Berbaum, Kennedy, Dunlap, & Nolan, 1990). Relatedly, "true" motion sickness in several different environments is not experienced at all by persons with bilateral labyrinthine deficits (Kellogg, Kennedy, & Graybiel, 1965; Kennedy, Graybiel, McDonough, & Beckwith, 1968), and labyrinthine defectives are also immune to sickness caused by vection (Cheung, Howard, & Money, 1991), but labyrinthine defectives can perceive vection (Cheung, Howard, Nedzelski, & Landolt, 1989). Therefore, the vection experience, which has been related to reports of presence and immersion in both VE and simulator exposures where sickness is also recorded (Hettinger et al., 1990; Kennedy, Stanney, Compton, Drexler, & Jones, 1999), constrains the conclusion one might wish to make about the origin of sickness (i.e., that sickness is caused by vection).

Simulator Sickness

As a topic of scientific inquiry, motion sickness has been studied primarily in its most popular forms: sea and air sickness (Reason & Brand, 1975) and space sickness (Crampton, 1990). Therefore, it is not surprising that when the ability to simulate vehicular motion was developed, a form of motion sickness unique to these conditions emerged. It has been referred to as simulator sickness, simulator aftereffects, or the simulator adaptation syndrome (Kennedy, Hettinger, & Lilienthal, 1990). The development of flight and automobile simulators appears to have been guided by the assumption that more realistic simulation (i.e., wide field-of-view visual displays containing highly detailed representations of environmental features) will result in faster and better training. Engineering talents have focused on creating realistic, high fidelity simulation environments, but empirical research has not indicated that increasing fidelity by "x" percent results in "x" percent increase in training benefit. A fundamental thesis of the current chapter is that while the effects of simulator realism and fidelity on training effectiveness are poorly understood or unknown, there is strong reason to suspect that increased realism may result in an increase in the incidence of simulator sickness. At present the psychophysical laws which govern the relationship between the richness or fidelity of visual imagery and training effectiveness are not well-known. However, in what follows, empirical evidence will be presented which indicates that as simulators have become more compellingly realistic and faithful in their representations of reality, the incidence of simulator sickness has increased. Not well recognized is that among the more serious problems presented by this syndrome is the potential for residual aftereffects (Crosby & Kennedy, 1982; Baltzley, Gower, Kennedy, & Lilienthal, 1988; Kellogg, Castore, & Coward, 1980; McGuiness, Bouwman, & Forbes, 1981; Ungs, 1989), including illusory sensations of climbing and turning, perceived inversions of the visual field, and disturbed motor control. Above all, the visually-related disturbances are more prevalent in simulator sickness than gastro-intestinal disturbances. In fact, simulator sickness bears a strong resemblance to the disturbances which individuals experience when wearing reversing, displacing, or inverting lenses mentioned above (Dolezal, 1982), or when exposed to rotating (Graybiel, Guedry, Johnson, & Kennedy, 1961) or tilted rooms (Witkin, 1943).

Space Adaptation Syndrome

Simulator sickness symptoms can also have much in common with reports of astronauts' experiences of the space adaptation syndrome (Homick, 1982; Parker, Reschke, Arrott, Homick, & Lichtenberg, 1985). For example, the vomiting in all these cases appears to have a sudden, sometimes unexpected onset, often without accompanying prodromal nausea (Thornton, Moore, Pool, & Vanderploeg, 1987), and dizziness is prominent. As pointed out by Casali (1986), the term "motion sickness" should perhaps not be used as a global description of sickness induced by simulators and Benson (1978) believes that the generic term should be motion maladaptation syndrome. Many simulators impart no physical motion at all, and yet sickness may still occur as a result of perceiving visual representations of motion (Hettinger et al., 1987; Parker, 1971). Currently, as VE systems have enabled provision of compelling sensations of self motion using visual scenes alone, symptoms of motion sickness have been increasingly reported in these systems as well (Durlach & Mavor, 1995).

Because the signs and symptoms which qualify for a diagnosis of motion sickness are diverse and because motion sickness can be caused by many stimuli, we find it helpful to refer to the malady as **polygenic** and **polysymptomatic** (Kennedy & Fowlkes, 1992). The diversity of causes and effects implies that while generalizable solutions will be difficult to obtain that will apply to all conditions or work on all symptoms, there is much ordered information in the scientific literature and reviews are available, (Kennedy & Frank, 1986; Money, 1970; Reason & Brand, 1975; Tyler & Bard, 1949), along with a field manual which suggests how to use devices in order to minimize symptoms (Kennedy, Berbaum, Lilienthal, Dunlap, Mulligan, & Funaro, 1987). The advent of sickness in VEs affords the opportunity to compare sickness rates and profiles in these environments to sea and space sickness.

Cybersickness In Virtual Environments

There is concern that continued development of VE technology may be compromised by the presence of motion sickness-like symptoms, known as cybersickness, which are currently being experienced by a significant proportion of VE users (Chien & Jenkins, 1994; Stanney, Mourant, & Kennedy, 1998). As VE systems were fielded, such ill-effects were compared with the symptoms of motion sickness reported in the 80s by military aircrew and NASA test pilots following their exposures to flight simulators (Frank, Kennedy, Kellogg, & McCauley, 1983; Kennedy, Lilienthal, Berbaum, Baltzley, & McCauley, 1989; Kennedy, Jones, Lilienthal, & Harm, 1993; McCauley & Cook, 1986). Significantly, the symptoms and aftereffects seen in connection with cybersickness and simulator sickness have elements in common with space sickness (Reschke et al., 1994; Paloski, Black, Reschke, Calkins, & Shupert, 1993) and other forms of motion sickness (Crampton, 1990). There do, however, appear to be some distinct differences between cybersickness and other forms of motion sickness (Stanney & Kennedy, 1997).

A good definition of virtual environments is available from Durlach and Mavor (1995, p. 18) who consider that a VE system "...consists of a human operator, a human-machine interface, and a computer. The computer and the displays and controls in the interface are configured to immerse the operator in an environment containing three-dimensional objects with three-dimensional locations and orientations in three-dimensional space. Each virtual object has a location and orientation in the surrounding space that is independent of the operator's viewpoint, and the operator can interact with these objects in real time using a variety of motor output channels to manipulate them." On the surface, this sounds very much like a definition of a simulator and we take no position whether one is a subclass of the other or the converse. The simplistic argument of the psychophysical linking hypothesis of Brindley (1960) is taken as analogous, which asserts that if the same neural experience occurs following two different stimulus conditions, then similar pathways may be involved in the action, and if different neural experiences occur, then perhaps different pathways were involved. If the symptoms of two forms of motion sickness

are very much alike, then one might argue for a common cause, even if they occurred in a different place, with different projection systems. The symptom profiles of VE and simulator systems, along with other forms of motion sickness, must thus be measured and compared to determine if cybersickness is distinctive or if it can be identified and treated with the same human factors solutions used for other forms of motion sickness.

One challenge in developing human factors solutions to this problem is to quantify and reliably determine the stimulus for the various forms of visually-induced sickness. Engineering tests of dynamic systems, such as flight trainers, routinely employ controlled inputs and measure them "end-to-end with visual/motion hardware response as the output" (Browder & Butrimas, 1981, p. ii). Such an approach is necessary to evaluate the engineering characteristics of a system. However, sickness in VEs is a person-centered problem. An identical VE device can have widely varying effects on different individuals. Given this interaction between users and VEs, determining the contribution of visual scene content, for example, to the incidence and severity of sickness, requires human-in-the-loop exposures. It thus becomes an issue of systematic measurement of human-centered phenomenon.

Measuring Sickness

Questionnaires

In our years of research investigating simulator sickness, forms of terrestrial sickness, and space motion sickness (SMS), we have employed a variety of techniques to document the incidence (Kennedy et al., 1989). The major tool utilized in these investigations was the simulator sickness questionnaire (SSQ) (Lane & Kennedy, 1988; Kennedy, Lane, Berbaum, & Lilienthal, 1993), which is currently in use at more than three-dozen laboratories and facilities. The early beginnings of this form of self-report questionnaire were: 1) Wendt (reviewed in Wendt, 1968) who, during World War II, performed research in an attempt to assess the continuum of motion sickness symptoms by employing a three point scale where "vomiting" was rated highest, then "nausea without vomiting", and finally "no symptoms"; and 2) Graybiel, Clark, and Zarriello (1960) who used a seven item symptom checklist. Subsequently, Kennedy and Graybiel (1965) also used a self-report technique that incorporated subjects' verbal symptom reports from studies of Coriolis sickness in the Slow Rotation Room. They expanded the symptom checklist to a total of 33 separate symptoms, from which a a five-point composite score was derived that was used to assess symptoms experienced during Slow Rotation Room studies (Kennedy, Tolhurst, & Graybiel, 1965). Other approach derived from this checklist, known as the Graybiel classification system (Lackner & DiZio, 1997), includes in the scoring the usage of signs as well as symptoms and requires an experimenter (Graybiel, Wood, Miller & Cramer, 1968).

Symptoms covered in both the Wendt and Graybiel et al. questionnaires include: Cerebral (e.g., headache), gastrointestinal (e.g., nausea, burping, emesis), psychological (e.g., anxiety, depression, apathy), and other less characteristic indicators of motion sickness such as fullness of the head. Responses to the questionnaire were made for each symptom using a five point Likert-type (1967) scale ranging from none to severe, and in some cases, yes or no. In later applications of the questionnaire, the five-point scale was expanded to study seasickness (Wiker, Kennedy, McCauley, & Pepper, 1979). The SSQ has also been used to study hurricane induced sickness in aircraft (Kennedy, Moroney, Bale, Gregoire, & Smith, 1972) and in storms at sea (Kennedy, Graybiel, McDonough, & Beckwith, 1968).

Psychometric Properties

While self report checklists have the obvious disadvantage of being subject to fabrication, they have a proven record of predictive validity, with a correlation between seasickness severity and objective

signs of vomiting of r = 0.73 ($p < .001$) (Wiker et al., 1979) and it is probably a safe, although nettlesome, assumption that questionnaire data are probably twice as reliable as the objective measures which have been developed to replace them. Ironically, these "objective" measures are sometimes validated against the self report score itself as the criterion. Questionnaires also exhibit reliability: 1) split half correlation for the SSQ for 200 subjects after a VE exposure is r = 0.80 [Kennedy, Stanney, Compton, Drexler, & Jones, 1999) and with the Spearman (1904, 1907) correction for test length, the full SSQ form is r = .89; 2) Yoo (1999) using a driving simulator, found reliabilities of r ~ 0.78 for the SSQ. It should be mentioned that the lack of reliability of objective measures of sickness is not only in the recording of the physiological response (e.g., EGG, pallor), but also in the physiological response system itself (viz., not all people get pale before they vomit).

Scoring

Currently, most information regarding cybersickness incidence and severity is available using one or another version of a controlled interview. In our early studies with this SSQ technique in military flight simulators, composite (i.e., total) scores showed that sickness was prevalent in nearly all fielded flight simulators of that era and appeared greatest in moving base simulators (Kennedy et al., 1989). Later, in order to improve on the metric properties of the questionnaire, a factor analysis was carried out (Lane & Kennedy, 1988), which revealed three clusters of symptoms. The clusters emerged logically and naturally from the factor analysis and were rational and consistent with theory, which made naming them very easy. The clusters were called: 1) Nausea; 2) Oculomotor; and 3) Disorientation (Kennedy, Lane et al., 1993; Kennedy, Lane et al., 1992). Scores on the Nausea (N) subscale are based on the report of symptoms that relate to gastrointestinal distress such as nausea, stomach awareness, salivation, and burping. Scores on the Oculomotor (O) subscale relate to eyestrain, difficulty in focusing, blurred vision, and headache. Scores on the Disorientation (D) subscale are related to vestibular disturbances such as dizziness and vertigo. A weighted average of these three factors comprises the Total Score, which is intended to reflect the severity of the symptomatology for an individual and can be used to index the ***troublesomeness*** of a simulator (see Table 1). On the other hand, we believe that there is also heuristic value in the profile or configural scoring of the devices that can be used to flag those individuals or systems with high-levels of symptoms.

Table 1. Categorization of symptoms based on central tendency (i.e., mean or median) using military aviation personnel in each simulator.

SSQ SCORE	CATEGORIZATION
0	No symptoms
<5	Negligible symptoms
5-10	Minimal symptoms
10-15	Significant Symptoms
15-20	Symptoms are a concern
>20	A problem simulator

Total Scores

The maximum total score possible on the SSQ is ~300 and normative data from flight simulators which were examined over a series of surveys carried out by the Navy and Army were aggregated to show the data in figure 1 (Gower, et al., 1987; Kennedy et al, 1994; Fowlkes et al 1990). Also shown for comparison are the results of 13 VE devices that are described in more detail below. There are two known constraints on these data: 1) the population of persons, over all the simulators shown in this figure, is made up more than 95% of military personnel and nearly all of them were pilots whereas the VE systems

generally use male and female college students; 2) the training regimes of these flight simulators differ from VE systems in that the former exposure durations are almost always greater than one hour and in some cases four hours – whereas VE exposures are usually less than one hour. However the sheer size of the data base (> 9000 exposures) and the regularity of the findings suggest that with the provisos mentioned one may use the data for normative purposes and for comparison with other devices. In the flight simulator studies, where paper and pencil versions of self report forms were employed and also where a computerized inquiry method was used for a large number of subjects (N = 6182; 10 simulators) certain regularities appear. Note for example in figure 1 that in the flight simulator data: 1) both cumulative frequency distributions grow at the same rate; 2) more than 40% of those exposed do not have any symptoms at all; 3) the average score is about 5; 4) 80% of those exposed have scores equal to or less than 20.

One application of the Total Score information, such as is found in Table 1, can be to serve in the creation of design criteria for building new (or modifying existing) simulators and VE devices. Therefore, despite the restricted range in response to sickness of the military aircrew who were used to comprise Table 1, using it as a basis, the acquisition engineer could require that a future or modified system should, perform, at the least, better against simulator sickness than current systems, so that for example, the future 75th percentile pilot user should suffer no more discomfort than the previous 50th percentile user. Also, after upgrading, simulators should be checked to determine whether the equipment modifications actually reduced sickness rates. Likewise, perhaps it is not too early to suggest that VE devices should at least be as benign to the college students who now form the research population, and they should not be made any more discomforted than the student pilots of twenty years ago. In other studies the application of Total Scores in indexing particular devices has been described (e.g., Kennedy, Lantham, Drexler, Massey & Lilienthal, 1997; Kennedy, Jones, Lilienthal & Harm, 1994). For the remainder of this chapter the focus is on the application of configural scoring.

Configural Scoring

Based on the thesis that motion sickness is often ascribed to a conflict between two sensory systems, Reason and Brand (1975) listed six types of sensory rearrangement that may produce motion sickness. They argue that the conflict may be between vision and vestibular inputs or between two vestibular inputs (cf., also Benson, 1978). Each of these two possibilities could have both sensory systems functioning (e.g., inertial inputs at sea, while watching the waves) or only one. Thus, on rational grounds they offer six types of sickness and we hypothesized that despite the obvious technical similarities of VE and simulators, it would be interesting to determine whether different devices can evince characteristically different symptom profiles, and then to compare the profiles of several environments to each other.

In figure 1, following factor analytic scoring (Lane & Kennedy, 1988), a generic simulator sickness configuration for a large database of Navy and Army simulators is shown. While most simulators resemble this profile, there are some differences that will be discussed later. However, in figure 2, this simulator sickness profile is compared to the profile from sea and space sickness and different forms or mixtures of symptoms are observed. As may be seen in this figure, seasickness, as one might expect, has a preponderance of nausea, and progressively lower levels of oculomotor and disorientation type reports. Conversely, space sickness has very little oculomotor symptomatology, significantly more nausea and moderate to severe amounts of disorientation.

The symptom mixture, if it could be shown to be reliably different in different simulators and reliably the same in one kind of simulator, might lend credence to the use of these symptom profiles in order to study better what is wrong with the simulator so that the fix could follow from rational distribution of symptoms. A look at one of our early groupings of simulators will allow us to make this point. In an earlier simulator report (Kennedy, 1996), the profiles of some moving base military (both

Army and Navy) helicopter simulators were grouped. In that work, it was noted that a consistent configuration is repeated (oculomotor high) and theorized that the profile might be indicative of differences between the stimulus to the human nervous system pathways that were excited or perturbed by the unique combination of stimuli which were presented by that class of device, and that following such a lead could later have payoff by improving understanding the process of motion sickness in these systems. Recall that the **level** of the symptoms (Total Score) would still be useful for signaling the seriousness of the problem in the simulator (see Table 1). However, now the Total Score is reflected in the total area occupied by the profile scores. Figure 3 displays the Total Scores for the same simulators depicted in figure 1. Thus for some purposes the Total Score may be preferred, if indexing the simulator to others for severity is the comparison sought. On the other hand, comparing the simulators for profile sameness and difference may contribute some meaningful diagnostic information.

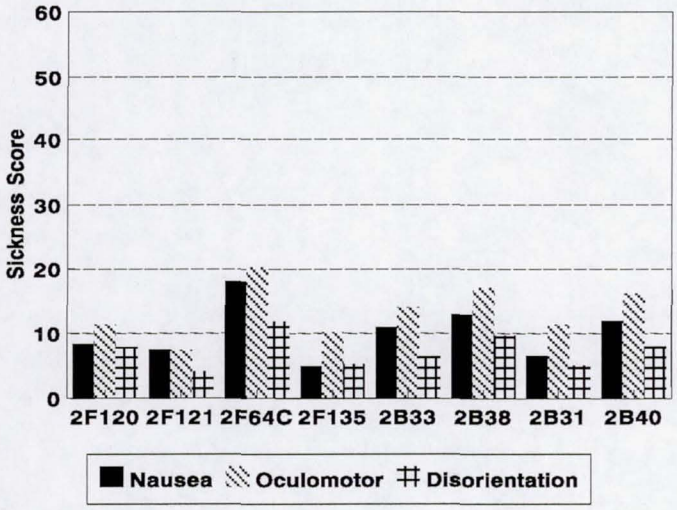

Figure 1. Symptom profiles in Navy and Army helicopter simulators.

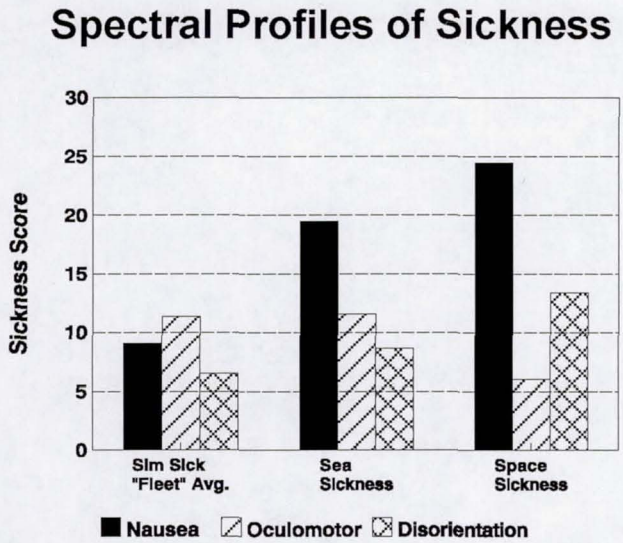

Figure 2. Comparison of simulator sickness and seasickness.

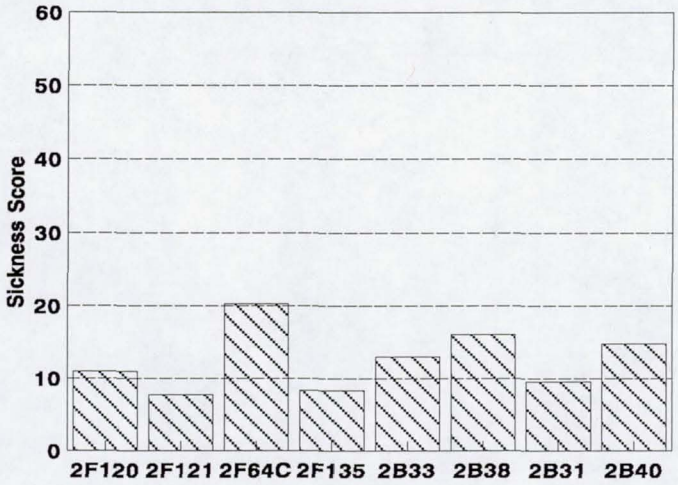

Figure 3. Total sickness scores for Navy and Army helicopter simulators.

Thus, when comparing figures 1 and 4, it may be seen that the simulator systems which had the highest incidence of oculomotor symptomatology in our database all tended to be helicopter simulators. All these helicopter simulators employed computer generated imagery over multiple cathode ray tube (CRT) displays that were often set at different physical distances from the operator's viewing position. Ebenholtz (1988) had made the point that such a configuration could lead to eye strain, and that is essentially what the oculomotor symptom complex appears to be showing. Admittedly, eye strain can be occasioned by many other factors, but using the information available here, one might look to common causes of eye strain in any situations where motion sickness symptoms appear to have a prevalence of this class of symptoms.

The opportunity to compare the symptom profiles (Nausea, Oculomotor, Disorientation) and overall level of sickness (Total Score) in questionnaires from eight different VE experiments was presented to us. We had carried out, in collaboration with three university laboratories, four experiments (1, 2, 4, & 5) using three different VE headmounted display (HMD)-based systems. Additionally, we had access to the data from four other experiments (two federal laboratories [3 & 7] and two other university laboratories [6 & 8]). Table 2 shows the pertinent details from the eight experiments with detailed hardware characteristics of each system. It may be seen that most of the experiments lasted 30 minutes, an extended period of time for purposes of immersion, but only one-fourth as long as the average simulator exposure time.

The purpose of the present study is to describe the results from these VE experiments. The symptom profiles and total sickness in the eight VE systems will be compared to the very large database from military flight simulators. Additional comparisons with both space motion sickness and seasickness will be made.

Table 2. Eight experiments using HMD-based VE systems.

Exp No.	Laboratory	HMD	Exposure Duration (min)	Program	N	Format (pixels)	Structure	Spot Size (ARC min)	Field of View (degrees)	Vertical Overlap
1	Univ. Cent FL (Orlando)	Kaiser E/O VIM 500 (Kennedy, Stanney, Dunlap, & Jones, 1996)	30	WorldTool Kit	34	710 x 225	Delta	3.38	40H x 30V	100%
2	Univ. Cent FL (Orlando)	i*glasses! (Kolasinski, 1996) [stereoscopic]	20	Ascent	40	789 x 230	Triad	~3	30D	100%
3	Army Personnel Research Establishment (Farnborough, UK)	Virtual Research Flight Helmet (Regan & Price, 1994)	20	Demo software	146	360 x 240	Not available	Not available	110H x 60V	Not available
4	Murray St.Univ. (Murray, KY)	i*glasses! (Kennedy, Jones, Stanney, Ritter, & Drexler, 1996) [stereoscopic]	40	Ascent	37	789 x 230	Triad	~3	30D	100%
5	Univ. of Idaho (Moscow, ID)	CyberMaxx 180 (Rich & Braun, 1996)	40	Heretic	23	789 x 230	Triad	~7	53H x 35V	100%
6	Univ. of Houston (Houston, TX)	Virtual Research VR-4 (Bliss et al., In preparation) [stereoscopic]	~20*	Solid Surface Modeler	55	742 x 230	Triads	8.10	48H x 36V	100%
7	U.S. Army Research Inst. (Orlando, FL)	Virtual Research VR-4 (Lampton et al., 1994) [stereoscopic]	20**	WorldTool Kit	57	742 x 230	Triads	8.10	48H x 36V	100%
8	George Mason Univ. (Fairfax, VA)	Virtual Research VR-4 (Salzman, Dede, & Loftin, 1995) [stereoscopic]	75***	Solid Surface Modeler	39	742 x 230	Triads	8.10	48H x 36V	100%

* Time dependent upon task completion; ** Repeated exposures used; *** Total time including breaks

METHOD

Apparatus

Virtual environment devices. The VE devices used for the experiments are currently commercially available over-the-counter without special modifications or provisions. One of the devices used is comprised of a computer game called Ascent, produced by Gravity for Virtual iO, which comes bundled with the i-glasses!. This system was used in two experiments [2 & 4] of differing duration (see Table 2). The HMD contained a head tracker that was engaged for all participants. The control device consisted of a standard mouse. The Ascent game was chosen because it met the following requirements: 1) it was easy to learn, uncomplicated, and moderately engaging; 2) the game is such that each participant received essentially the same stimulus, and the game can cycle continuously for a specified amount of time; and 3) previous testing revealed that this game had the potential to induce discomfort in some individuals (Kolasinski, 1996), possibly due to the active head movements required to play. The other devices listed in Table 2 entail similar combinations of HMDS and software, but each system had unique characteristics. A full catalogue of every item on which these devices and programs differed would be too lengthy for this chapter, but that does not mean that these differences are considered insignificant. At this stage of our knowledge, it is not yet known what features to list and studies such as are reported here will help to focus on what features should be reported.

The procedures for most of the eight experiments were the same. That is, while engaged in the VE task, participants were seated in a chair to allow 360-degree viewing of the virtual environment. Lights were turned off in the room while the participant was immersed in the VE to reduce glare and reflections within the HMD. Participants were usually administered questionnaires prior to exposure. Participants were exposed to the VE for the durations specified in Table 2. The virtual task activities generally involved navigation throughout the VE and virtual object manipulation via the mouse. The SSQ was administered immediately after exposure.

RESULTS

Simulator Sickness Questionnaire

Total scores

Figure 4 shows the average Total Score in the eight VE devices from Table 2. The average score over all the devices is at about 30 on the Total Score scale but the range is broad, from 19-55**Error! Reference source not found.**. Using the same Total Score, the military helicopters show an average score below 10, indicating substantially lower severity in military helicopter flight trainers. Figure 5, also for comparison, lists three examples from NASA's space sickness program. The first two are laboratory tests for assessing motion sickness susceptibility (Coriolis Sickness and Preflight Adaptation Trainer) and understandably have expectedly high scores, since they are used experimentally to produce sickness. The third, space sickness, is based on

the reports of 85 persons (astronauts) who actually traveled in space, and the incidence here is between the average for simulator and for VE exposures. To provide a context in a single figure we have also added to figure 5 the average of: all the Army helicopters, all the Navy/Marine Corps helicopters, and all the VE systems. It would appear that VE users report more sickness than military flight simulators and astronauts during space travel, but not as much as with NASA's provocative tests of space sickness.

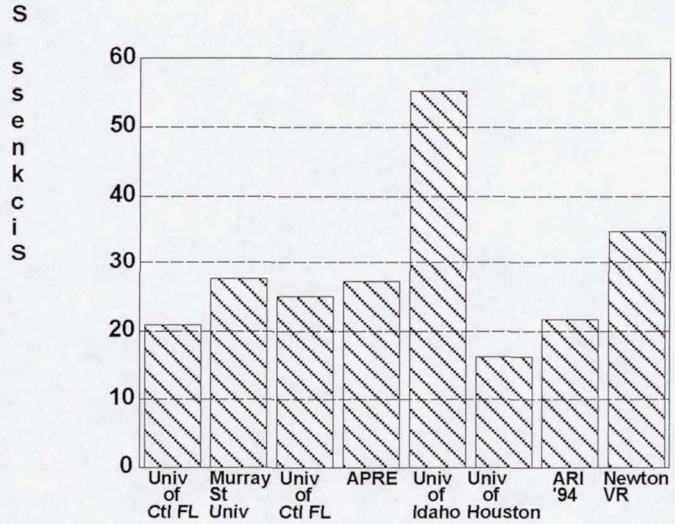

Figure 4. Total sickness scores for eight different VE devices.

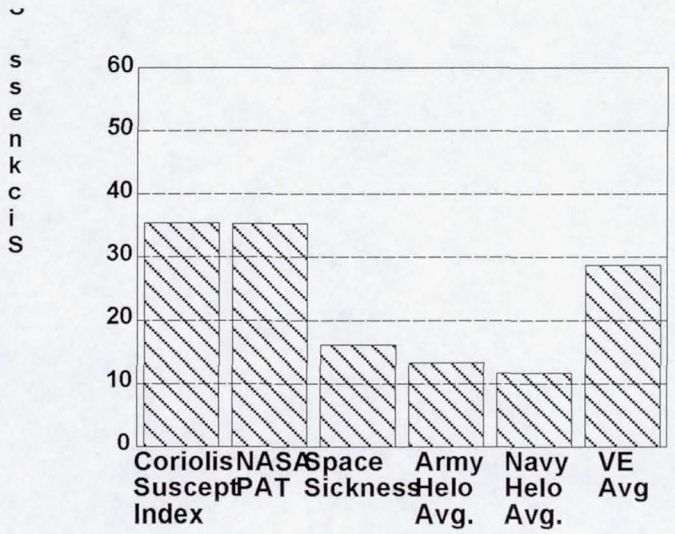

Figure 5. Total sickness scores for NASA's space sickness program, military simulators, and VE averages.

Figure 6 shows the same systems according to their three-factor configural-scoring basis (i.e., Nausea, Oculomotor, and Disorientation). First, of the eight VE systems, there appear to be two distinctly different profiles. The more common (5 VEs) show less Oculomotor symptoms than the other two sets of symptoms. This is referred to as VE type A. The second group (3 VEs),

referred to as VE type B, all produced by the same manufacturer (i.e., Virtual Research), show relatively less Nausea, but are otherwise consistent with the type A VE. That is, all VE systems appear to exhibit a significant amount of Disorientation and lesser Oculomotor symptoms. Type A VE shows significantly more Nausea than type B does. On the other hand, it may be seen that the helicopter simulators in figure 1 also have a very distinctive profile. The profile shows the most prominent symptom cluster to be Oculomotor, which is different from the profile of VE sickness (Figure 6). As a summary comparison, we show in Figure 7 the average simulator (Army and Navy) sickness, the average VE sickness (type A & B), and three types of space sickness examples (actual and laboratory induced). The actual and experimentally produced space sickness examples have a profile that resembles VE type A (high Nausea and Disorientation, low Oculomotor disruption) and to a lesser extent VE type B, which has far less Nausea. Again it should be obvious the Army and Navy helicopter simulator symptom profiles are distinctly alike, and are different from the other five types of sickness.

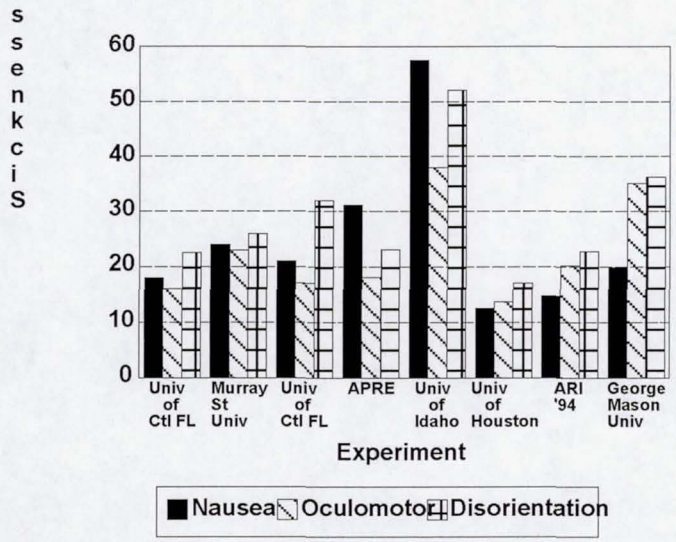

Figure 6. Symptom profiles in eight different VE devices.

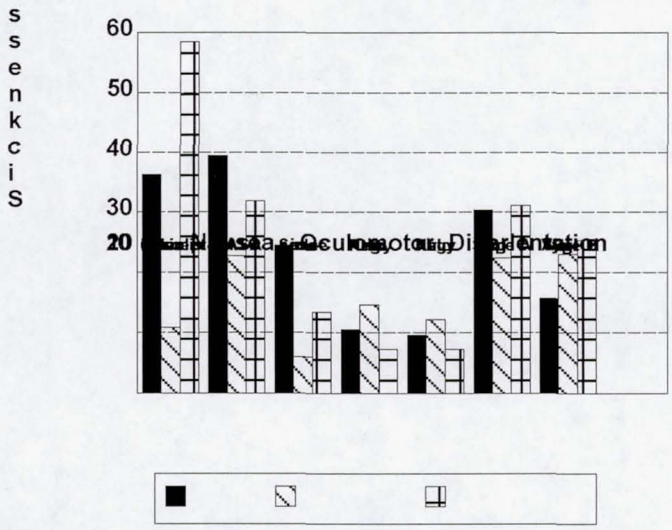

Figure 7. Symptom profiles for three types of space sickness and average simulator and VE sickness.

As these profiles demonstrate, simulator and VE sickness are very different. Simulators tend to have disproportionately high oculomotor symptomatology (and low disorientation reports), while VEs tend to have high disorientation symptomatology (and moderate or low oculomotor reports). Additionally, VEs generally have higher total sickness scores, regardless of the subscale profiles. Given the lower score of simulators, the moving base devices seem to exhibit relatively more nausea, although some VE systems show high nausea too.

Several "group membership" procedures were performed to identify different symptom clusters and determine how well each study exhibited such clustering. They basically consist of discriminant and chi-square analyses.

Discriminant analyses were conducted in order to determine how well group membership on known characteristics could be predicted from the subscales (nausea, oculomotor, and disorientation). Class separation was performed on the basis of very straightforward characteristics, usually binary in nature: moving base vs. fixed base; fixed wing vs. rotary wing; HMD vs. dome projection; monoscopic vs. stereoscopic imagery; and simulator vs. virtual environment. The scores used in the discriminant analyses were the average scores for all participants in each study, yielding one set of numbers for each device analyzed. The simulator vs. VE comparison yielded strong results, however, it is not known how much of that separation is due to the symptom profiles and how much is due to the difference in symptom magnitudes between the two device types.

Another analysis was done to assess how well each participant's profile in a study matches the profile for the study overall. A chi-square test was used to make this assessment. Originally, the study was divided into all six possible profiles (N > O > D, N > D > O, O > D > N, O > N > D, D > N > O, and D > O > N), but for simplicity, only three categories were used for this analysis. The categories chosen were simply based upon which symptom was the greatest (N, O, or D). This yielded three possible categories (excluding "ties" for highest symptoms). Participants reporting no symptoms were discarded from this analysis. The results are presented below. The first column indicates the study and the study number, followed by columns for nausea (N), oculomotor (O), disorientation (D), chi-square, and the total number of cases. The three subscales (N, O, and D) have two lines of data for each study: the first line contains the **number** of participants having that profile, while the second line indicates what **percentage** of participants in that study have that profile. Data are presented for various simulators (Table 3), VE systems (Table 4), and simulators that utilized an electronic version of the SSQ entitled BESS (Table 5).

Table 3. Symptom profiles for various simulators.

Study	N	O	D	Chi Sq.	Total N
2E6 - '84	3	2	1	.607	6
	50	33.3	16.7		
2E7 Lemoore '84-	27	15	10	.012	52
	51.9	28.8	19.2		
2F110 Miramar '8	6	19	6	.004	31
	19.4	61.3	19.4		
2F112 Miramar '8	7	9	1	.047	17
	41.2	52.9	5.9		
2F117 New River	30	82	22	.000	134
	22.4	61.2	16.4		
2F132 Lemoore '8	2	10	1	.004	13
	15.4	76.9	7.7		
2F87F Bruns. '84	5	44	4	.000	53
	9.4	83	7.5		
2F87F Jax '86	14	24	3	.000	41
	34.1	58.5	7.3		
2F121 New River	41	43	10	.000	94
	43.6	45.7	10.6		
CH-53E Tustin	28	58	12	.000	98
	28.6	59.2	12.2		
CH-53E NewRiver	10	18	7	.000	35
	28.6	51.4	20		
2F64C Jacksonville	97	152	39	.000	288
	33.7	52.8	13.5		
TH57C In-plant	13			.000	13
	100				
Whiting '88 - TH	16	43	10	.000	69
	23.2	62.3	14.5		
ARMY AH-1 Ft. Ru	19	33	8	.000	60
	31.7	55	13.3		
ARMY UH-60 Ft. R	24	42	8	.000	74
	32.4	56.8	10.8		
ARMY CH-47 Ft. C	6	40	2	.000	48
	12.5	83.3	4.2		
ARMY AH-64 1987	83	128	10	.000	221
	37.6	57.9	4.5		
2F120 New River	4	9	1	.030	14
	28.6	64.3	7.1		
Tustin '91 CH-46	6	12	3	.050	21
	28.6	57.1	14.3		
Tustin '91 CH-53	9	16	1	.020	26
	34.6	61.5	3.8		
Whid.,'91-A-6E	4	14	8	.054	26

	15.4	53.8	30.8		
Whid.,'91-EA-6B	9	9	1	.026	19
	47.4	47.4	5.3		
Tustin '92 CH-46	3	10	3	.080	16
	18.8	62.5	18.8		
Tustin '92 CH-53	2	2	1	.607	5
	40	40	20		
Whid.,'92-EA-6B	2	5	1	.197	8
	25	62.5	12.5		
Mayport '93 SH60	5	36	6	.000	47
	10.6	76.6	12.8		
Whiting'93 TH-57	4	52	19	.000	75
	5.3	69.3	25.3		
Ocoee I '94	3	4	4	.913	11
	27.3	36.4	36.4		
Ocoee II '94	11	8	5	.325	24
	45.8	33.3	20.8		
VTRS '94 FAST		45	2	.000	47
		95.7	4.3		
2F87(J)	8	13	4	.087	25
	32	52	16		

Table 4. Symptom profiles for various VE devices.

Study	N	O	D	Chi Sq.	Total N
Kolasinski **VE**	11	9	14	.572	34
	32.4	26.5	41.2		
Murray VE	13	12	16	.728	41
	31.7	29.3	39		
Idaho VE	8	3	8	.268	19
	42.1	15.8	42.1		
Bliss VE	8	13	13	.479	34
	23.5	38.2	38.2		
Stanney VE	8	9	7	.882	24
	33.3	37.5	29.2		
ARI 1a	5	13	22	.004	40
	12.5	32.5	55		
ARI 1b	9	19	6	.017	34
	26.5	55.9	17.6		
ARI 1d	6	25	7	.000	38
	15.8	65.8	18.4		
ARI 2.1	4	8	11	.200	23
	17.4	34.8	47.8		
ARI 2.2	15	23	29	.110	67
	22.4	34.3	43.3		
ARI 3.1	10	16	17	.368	43
	23.3	37.2	39.5		
ARI 4.1a	4	12	2	.009	18
	22.2	66.7	11.1		
ARI 4.1b	3	12	4	.021	19
	15.8	63.2	21.1		
Kay\Sue VE	112	59	121	.000	292
	38.4	20.2	41.4		
Deb Harm SSQ 5/9	35	5	38	.000	78
	44.9	6.4	48.7		
Dark Focus 10/94	56	158	48	.000	262
	21.4	60.3	18.3		
Dark Focus NASA	17	112	14	.000	174
	9.8	64.4	8		
Jim May 9/98	177	78	325	.000	580
	30.5	13.4	56		

Table 5. Symptom profiles for various simulators (using BESS).

Profile	N	O	D	Chi Sq.	Total N
TH57C - Whiting	958	375	379	.000	1712
	56	21.9	22.1		
CH-53E New River	6	2	13	.012	21
	28.6	9.5	61.9		
CH-46 Tustin '91	96	107	149	.001	352
	27.3	30.4	42.3		
CH-53 Tustin '91	36	45	45	.526	126
	28.6	35.7	35.7		
2F114 - Whidbey	67	88	92	.112	247
	27.1	35.6	37.2		
2F143 - Whidbey	14	19	23	.336	56
	25	33.9	41.1		
CH-46 Tustin '92	115	95	129	.075	339
	33.9	28	38.1		
CH-53 Tustin '92	7	3	10	.157	20
	35	15	50		
2F143 - Whidbey	33	36	30	.761	99
	33.3	36.4	30.3		
CH-46 N.Island	110	111	183	.000	404
	27.2	27.5	45.3		

DISCUSSION

With flight simulators and VEs both being visually interactive environments, one might expect their ill-effects to be the same. The data reveal that these two types of systems are different on two accounts:

1) Based on the results of this study, the **level** of symptoms produced by VE systems are statistically higher ($P < .0001$) than those engendered by flight simulators. More specifically, Figure 3 indicates that, on the average, flight simulators have Total Scores ranging from 8 to 20, with most systems being 10 or under. Figure 4 indicates that the Total Scores for VE systems are considerably higher, ranging from 19 to 55. There are the obvious physical differences between these two types of systems. However, it should be pointed out that nearly all the persons used in the simulator data are military pilots who are self-selected, have more experience with novel motion environments, and may be more likely to under report symptoms, whereas in VE systems the participants were mostly college students. Whether this is a true difference in device or population remains to be investigated. In either case an interesting finding.

2) The symptom **profiles** of these systems are quite distinguishable. First, Figure 7 demonstrates that, as a family, the flight trainers (all moving base, helicopter simulators from U.S. Army, Navy and Marine Corps training centers which use multiple cathode ray

tube display systems) have distinctively different profiles of sickness from space and VE sickness. The simulators show proportionately more reports of Oculomotor disturbance when compared to Nausea and Disorientation, whereas space sickness (see Figure 2) and five of the eight VE devices (see Figure 6) show a reverse of the simulator sickness pattern (i.e., proportionately more Nausea and Disorientation when compared to Oculomotor). In nearly all the simulator data, the prominent symptom cluster (oculomotor) is statistically verifiable, and in five VE devices Disorientation is the statistically verifiable prominent symptom cluster. These results demonstrate quite convincingly that flight simulators and VE systems produce different patterns of symptomatology. In addition, VE systems produce higher levels of all three-symptom clusters than flight simulators. But why?

Although there are not sufficient data to conclude confidently, we believe:

a) For systems with relatively high **Oculomotor** disturbances, one should predictably focus on the visual display system. Head-mounted displays can have a distorted field-of-view that may drive such visual disturbances, although in our experience persons in multiple CRT systems report more eye strain, a key factor in the Oculomotor symptom cluster. These disturbances can be due to several issues, including: optical displays imaged at infinity but at different distances (Ebenholtz, 1988); magnification differences between the right and left channels; right and left channel relative image rotation; off-axis views; relative misalignment between the optic axis of the left and right channels; inconsistent focus adjustment between channels; and luminance differences between channels, such as bi-ocular versus binocular displays (Rushton, Mon-Williams, & Wann, 1994).

b) The high **Disorientation** may come about in VEs for several reasons. First, there are rotation-induced effects because the head is capable of moving side to side. These movements, which often exhibit noticeable lag, can also engender pseudo-Coriolis stimuli (Dichgans & Brandt, 1973). Second, because of a difference in visually displayed perception and the fact that a person is seated while he/she is provided visual cues that produce self motion, this could produce another VIMS problem (Hettinger & Riccio, 1992). In flight simulators persons are also seated—but they would be in the real aircraft. In VEs one is seated but usually the simulation is of walking. One might also focus on position tracking systems that track a user's head, hand, or other body part to create virtual worlds from the user's perspective. When a position tracking error occurs there is a mismatch between the visual space perceived from the VE and the perceived proprioceptive (felt position) cues. The cues from the visual system seem to dominate, thus causing cue conflicts, which may lead to nausea and/or to disorientation. Further support for these possible explanations of why flight simulators and VE systems produce different symptom patterns may be found by examining conditions present in space flight. As noted earlier, the symptom pattern produced by a number of VE systems (type A) is identical to the symptom pattern associated with SMS. In the microgravity environment of space flight, the primary sensory

information about movement through and position inside the Shuttle is visual. Particularly during the first few days of the mission, when SMS symptoms are often present, astronauts increase their reliance on vision for self-motion and position information (Harm & Parker, 1993; Reschke et al., 1994). One might argue that there is a mismatch between visual and proprioceptive cues similar to that described above for VE systems. In addition, there also may be similar mismatches between visual and inertial cues in VE systems and the space flight environment.

c) The lowered **Nausea** in VE type B compared to type A could relate to the better computational capabilities of these Virtual Research systems and/or to lowered transport delays of VE type B systems found in our study.

Admittedly, the above items (a-c) are speculative, but they are offered to suggest that the cybersickness experienced in VEs at least may be driven by different technological factors than the simulator sickness experienced in flight simulators. Arguably, if pursued, these symptom profiles may signal what aspects of the equipment should be improved in order to minimize sickness rates.

In summary, *using the factor analytic approach (Kennedy, Lane, Berbaum, & Lilienthal, 1993), if sufficient individuals are studied, it may be possible that the distribution or configuration of the three factors may turn out to be consistent within a given simulator or VE device and different between simulators or VE devices. If so, then perhaps this might provide a method whereby the many different causes of cybersickness can be delineated. Therefore, while Total Score differences in VE devices may index the level of the problem, differences in profile or configuration, REGARDLESS OF LEVEL OF SICKNESS, may signal the nature of the cause of sickness in that VE device.* Thus, this SSQ factor analytic scoring technique has promise, not only for evaluating total incidence of sickness, but also for determining the contribution of symptom clusters. As reported in this chapter, there is evidence that a higher than average incidence in a particular cluster can provide an indication as to which equipment feature(s) is the source of the problem.

Additional Concerns

The results from this study indicate that exposure to a VE system may result in high levels of ill-effects. Theories (Oman, 1991; Reason & Brand, 1975; Riccio & Stoffregen, 1991) suggest that during, at least, the first exposure, this illness presumably is triggered prior to adapting to the altered environment. These ill-effects are usually characterized by symptoms referable to the autonomic nervous system (see Figure 8). The symptoms may outlast the VE experience itself and aftereffects may continue with decreasing intensity for some time after exposure. Thus, both sickness and aftereffects are concerns. Up to now, sickness has been the primary focus in simulator sickness, but it may be the lesser of the two human factors concerns with VE technology.

The aftereffects from VE exposure need to be examined. For example, if the VE experience is lengthy or repeated, participants can be expected to adapt to the rearranged sensory cues provided by the VE that are thought to cause sickness. In these cases, sickness symptoms like nausea and sweating may only be observable during initial exposures. But after protracted single (>.5 hours) or many distributed exposures, neural adaptation may serve to weaken the sickness inducing aspects of the VE exposure. However, if these adaptations to a rearranged VE take place, in the form of neurosensory and sensorimotor learning, when the individual steps out of the VE he/she may not be aware that neuro-physiological readaptation to baseline may then need to take place. We believe it is a mistake to think that subsidence of the motion sickness symptoms, through adaptations, is likely to result in lessening of other post effects like balance disturbances. In fact, quite the opposite is more likely. That is, with adaptation the VE user will experience fewer symptoms of motion sickness, but may continue to exhibit sensorimotor disturbances (i.e., degradation of eye-head and eye-hand coordination, postural instability, and perceptual illusions) for some time beyond recovery of sickness symptoms. These two processes, motion sickness and sensorimotor readaptation, probably involve different central nervous system pathways. Figure 8 shows a model of how this might occur and also is meant to show that when the VE experience ends and participants return to a normal environment, they may show disturbances consistent with readaptation to the normal environment and they may not feel sick (i.e., they may feel fine but not be able to walk with steady strides due to ataxia).

This second (readaptation) process may follow a very different time course than adaptation. First, it is not evidenced during the VE exposure but after it. Second, the disturbance may develop and grow in the period following VE exposure and continue for quite some time. Stated differently, the time courses of sickness, adaptation, and readaptation may all be different. Moreover, the individual symptoms and response mechanisms of sickness and adaptation respectively may each follow their own time courses. This state of affairs makes successful measurement of these events "very dicey" to say the least.

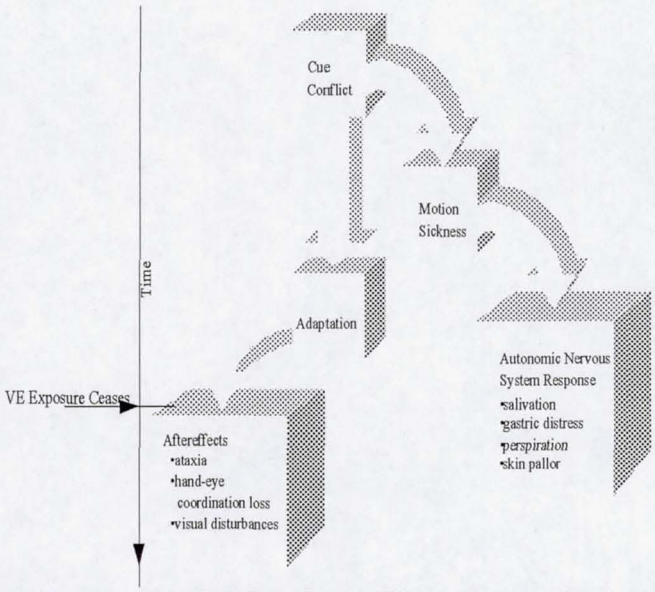

Figure 8. The time-course of deleterious effects from a single VE exposure.

Moreover, either sickness symptoms or sensorimotor adaptation or both may occur. This was observed in several of the VE studies reported in Figure 4 and Figure 6. For example, Kennedy and Stanney (1996a) found that sometimes postadaptation phenomena in the form of postural disruption can occur even when sickness is absent. Alternatively, ataxia may not be seen to a significant degree, but symptoms of sickness may be present. In our experience, it is possible that any of the post-adaptation phenomena (i.e., aftereffects) may occur as a sole manifestation of exposure. This means that it is imperative that managers (scientists, developers) of VE systems evaluate users before and after exposure, and use this information to guide their activities after completion of the exposure. This pressing need, in our opinion, is brought on by the potential for hazard and related products liability concerns (Kennedy & Stanney, 1996b). If injury occurs subsequent to VE exposure, and the VE system is adjudged "defective" because it occasions injury, and the responsible person or entity knew, or should have known it was defective, liability can be attached to any individual or business who profited from the defective technology. In the U.S., for legal liability to be found, a product "defect" which is "unreasonably dangerous to the user" must be proven. The VE system must be considered "dangerous to the extent beyond that which would be contemplated by the ordinary consumer." This is a likely scenario since, while most users may be aware of the overt autonomic nervous system response (see Figure 8) to VE exposure, predictably few are aware of the potential for deleterious physiological aftereffects that could disrupt normal human performance. These subtle changes may be latent and therefore not obvious to the average user. We therefore believe that developers of VE systems should take steps (warnings, certification tests, checklists, etc...) to assure that their users are safe to reenter the real world after exposure to the virtual environment. Such proactive steps could minimize developers' legal liability.

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