Australian Government
Department of Defence
Defence Science and
Technology Organisation

Side Effects of Virtual Environments: A Review of the Literature

Judy Barrett

Command and Control Division
Information Sciences Laboratory

DSTO-TR-1419

ABSTRACT

Cybersickness symptoms are the unintended psychophysiological side effects of participation in virtual environments. Symptoms can occur both during and after participation, thus having implications for health and safety, user acceptance, and overall system effectiveness. Just as for other visually induced motion sickness, cybersickness is believed to result from sensory and perceptual mismatches between the visual and vestibular systems, and can be considered as a problem of adaptation to altered environments. Symptoms can be grouped into three dimensions: nausea, disorientation or postural instability, and visual symptoms. Numerous factors relating to the individual participants, the virtual reality system and virtual environment used, and the task carried out, can affect either incidence or severity of cybersickness. Taking account of these factors may avoid or minimise symptoms. This report reviews the literature on cybersickness, simulation sickness, and the relevant research on motion sickness, considers measures that have been proposed to manage and treat cybersickness, and identifies areas where more research is needed.

Published by

DSTO Information Sciences Laboratory
PO Box 1500
Edinburgh South Australia 5111   Australia

Telephone: (08) 8259 5555
Fax: (08) 8259 6567

AR-012-747
May 2004

APPROVED FOR PUBLIC RELEASE

Side Effects of Virtual Environments: A Review of the Literature

Executive Summary

Virtual environment (VE) technology has the potential for innovative applications within defence. The Future Operations Centre Analysis Laboratory (FOCAL) at DSTO Edinburgh is one new facility where these applications can be explored. Yet although VE technology is developing rapidly, its progress may be hampered by the side effects experienced by participants. These side effects, which have been most studied as simulation sickness in flight simulators, include a variety of symptoms ranging from nausea and disorientation to eyestrain or blurred vision. Different VEs may give rise to differing symptoms of differing severity. Symptoms can occur both during and after participation in the VE, and therefore raise concerns for health and safety as well as for the overall effectiveness of the VE application. An understanding of these side effects, their causes, and factors that influence their incidence or severity, may allow symptoms to be avoided or minimised for a given VE.

The present report reviews the literature on the side effects of VEs (cybersickness), including simulator sickness, as well as relevant research on motion sickness. Symptoms of cybersickness can be grouped into three dimensions: nausea or stomach discomfort, disorientation or postural instability, and visual symptoms. It is commonly accepted that the symptoms of nausea and instability result from sensory conflicts, in which conflicting position and movement cues are received by visual and vestibular systems. However, more realistic displays may lead to increased rather than decreased symptoms. Additional visual symptoms can occur with some displays, particularly 3D displays. Occurrence of side effects may be influenced by a large number of factors that involve individual differences, system and task variables. The report discusses these factors, as well as measures that could be taken to reduce side effects. Apart from studies of simulator sickness the research literature on VE side effects is still small. Given the wide variability among VEs, considerable research is still needed to understand VE properties that may induce symptoms, and measures that could be taken with either the VE design or preparing individual participants so that symptoms may be avoided or minimised.

Author

Judy Barrett
Command and Control Division

Judy Barrett has degrees in psychology, applied mathematics, and social administration. Since re-joining DSTO in 1998 she has worked on the Future Operations Centre Analysis Laboratory (FOCAL) task, investigating potential side effects for participants using the system. She has also worked on the Theatre Situation Awareness task, investigating user satisfaction with software tools.

Contents

1. Introduction

1.1 Virtual Reality and Virtual Environments

Virtual reality (VR) has considerable potential for applications in a number of fields, including education and training, medicine, industry, commerce, space, scientific research and the entertainment industry. More importantly in the context of this report, VR holds potential for new applications in defence, where at present the best known use of VR is in the specialised and currently well researched flight simulators. The innovations made possible by the use of VR technology should be explored thoroughly so that defence is better positioned to meet future challenges. Yet despite its promise, VR both as a technology and a field of research is still immature. Thus at the same time as novel uses for VR are being investigated, considerable systematic research must also be carried out for its full potential to be realised.

At present a range of previously disparate disciplines, from technology through to the humanities, is contributing to the field of VR. The early stage of development and interdisciplinary nature of VR are partly responsible for the present lack of agreement even on basic definitions and terminology. This situation is complicated by the overuse and sometimes-inappropriate use of the terms "virtual" and "virtual reality", which at times have been applied to almost anything associated with computers. However, most writers in the field now use the term VR to apply to those systems used to generate virtual environments (VEs) to be experienced by participants. The VEs are then characterised by a number of properties: they are computer generated, interactive in real time, immersive or at least partially immersive, and generate feelings of presence or involvement. Interaction and navigation around the VE should be intuitive, and objects in the VE may be perceived as 3-dimensional (3D) [Durlach & Mavor 1995; Heim 1998; Machover & Tice 1994; Wilson 1997].

The VR systems available today comprise a heterogeneous group. Perhaps the simplest is the stereoscopic desktop, which produces an illusion of 3D depth from a conventional screen viewed through polarising filters or shutter glasses. Immersive workbenches or tables use a similar system to produce a larger 3D display. A BOOM (binocular omni-oriented monitor) uses a display on a flexible arm so that the user can manoeuvre it into position. Head mounted displays (HMDs) consist of screens and lenses fitted into a helmet or goggles, with a display that may be monocular (display seen by one eye only), biocular (both eyes view a single screen), or stereoscopic (each eye views a different screen or image, giving additional depth cues). HMDs often have head tracking and earphones to create a more immersive environment. Augmented reality systems such as head-up displays have information from the computer system overlaid onto a view of the real world. Larger VR systems employ wall-mounted or large curved screens to display either 2D or 3D images. For greater immersion images may be projected on to the walls and ceiling of a small room as in the CAVE (CAVE Automatic Virtual Environment), in which the user wears stereo glasses and a head tracking device. Finally, simulators are usually included as a type of VR system. This list is by no means exhaustive, and the number of variants on these systems is increasing rapidly. While there are many research issues, and in particular human factors issues, common to these varying systems, their wide variety often makes generalisations and comparisons between systems difficult [Heim 1998; Wann & Mon-Williams 1997; Wilson 1997].

This report is intended to review certain VR issues relevant to the Future Operations Centre Analysis Laboratory (FOCAL). FOCAL is being established to explore the use of state of the art technology, including VR, for aiding the future commander's situation awareness, mission planning and decision-making capability. The first phase of FOCAL provides collaborative semi-immersive viewing and interaction by means of a wide field-of-view curved screen that can display either mono or stereo graphics. Plans for later phases of FOCAL include a virtual table and head mounted displays. As differing VR systems will eventually be used within FOCAL, literature relevant to the range of VR systems will be reviewed here. This report will touch briefly on the range of human factors issues relevant to VR systems and VEs. It will then consider in detail one of these issues, that of cybersickness, or the side effects and after effects of participation in VEs.

1.2 Human Factors Issues in Virtual Environments

The early research and literature of VR and VEs focussed primarily on the development and applications of the technology itself. More recently attention has been drawn to issues of useability and human factors. Given the emphasis of VEs on the experience of human participants these issues should be considered from the early design stages, as human capabilities and limitations can greatly influence VE effectiveness. For example, constraints are imposed on VE design by human sensory, perceptual and motor limitations. Human performance efficiency in a VE may be influenced by a number of factors relating to the design of the environment, the task to be performed, and characteristics of the individual user. One feature of design, navigational complexity of the VE, can impede performance. Indeed, navigation and orientation within a VE are important issues, as users may easily become lost in a complex VE, just as some users at present become lost in the simpler desktop environment of hierarchical menu systems. The method of navigation can also affect the amount of sickness experienced during and after immersion [Chance, Gaunet, Beall, & Loomis 1998; Howarth & Finch 1999]. The task to be performed should be suitable for VE representation, as only some tasks benefit from the use of stereoscopic 3D visualisation, real-time interactivity and multi-sensory feedback. Some types of task can also cause more side effects [Mon-Williams & Wann 1998]. Individual differences in users can affect performance in the VE, the most notable difference being in degree of experience. However, individuals also differ in aptitudes such as spatial visualisation, orientation, spatial memory and spatial scanning, each of which can affect performance. Individuals differ too in sense of presence and in susceptibility to the side effects that will be discussed in this report [Stanney, Mourant, & Kennedy 1998].

Another major research issue is the nature of the participant's interaction with the VE. In contrast to human-computer interaction (HCI), which is generally from an exocentric perspective, interaction with the VE is generally more from an egocentric perspective, so that what has been learned from HCI studies may have limited applicability. Many VEs can provide visual, auditory and haptic information, which raises issues of integration and redundancy. Also, the most effective modes of feedback in a VE task may be different from those in a real world situation. Immersive VEs require the representation of participants and of agents (the development of avatars), not only for realism but to give appropriate visual cues to participants. Overall, VEs need design metaphors suited to their characteristics. Some metaphors already suggested include VR sliders (3D equivalents of scroll bars), map cubes (3D maps of the participant's virtual vicinity), tow planes (participants are towed through the VE by a virtual object). Portals and spirals have been suggested as VE counterparts of windows [Stanney et al. 1998; Wilson 1997]. The method of interaction between participant and the VE can also influence the occurrence of side effects. Because VR technology provides a set of relatively new and interrelated cognitive and physical interfaces, some authors have suggested that devising appropriate interfaces for VEs involves a paradigm shift in interface design generally [Wilson 1997].

An important area of concern is that of health and safety generally. Some researchers have focussed on the ergonomics of HMDs. They have raised issues such as the risk of shoulder and head discomfort and strain, and unusual demands on both bodily posture and the relevant human visual mechanisms. Participants may have difficulties using 3D hand-held input devices, or even fear becoming entangled in the connecting cables [Nichols 1999; Wilson 1999]. Other authors have raised social and ethical issues. Concern has been expressed over possible behavioural effects of exposure to violent VEs, and of potential problems such as dissociation, misplaced locus of control, or retreat from reality [Wilson 1996]. These are similar to concerns raised with television, or with computer and video games [Stanney et al. 1998; Wilson 1999]. A major area of concern in the health and safety area is that of the side effects and after effects of VE exposure, or cybersickness, which as already indicated is related to a number of other human factors issues. The literature on cybersickness is reviewed in this report.

1.3 Side Effects of Virtual Environments

Since the early 1990s reports have appeared documenting cybersickness, the psychophysiological side effects and after effects of participation in VEs. Although the VR systems studied and the methodologies used have varied, the effects observed are consistent with the extensive literature on simulator sickness, the sickness resulting from the use of flight simulators. It is important to understand the incidence and precipitating factors of cybersickness, as potentially it affects performance in the VE and has implications for the safety of participants both during and after VE exposure.

To date the research literature on cybersickness specific to VEs is not comprehensive, with most studies concentrating on the more affordable low end HMDs. However, many insights may be obtained from the extensive research literature on motion sickness, simulator sickness and the psychophysiological effects of other perceptually altered environments.

To date researchers have been divided over whether the problem of cybersickness can be solved with future improvements in technology. Most VR technologists and developers have assumed that it will be solved, and certainly changes such as improvements in position tracking, better feedback, and faster updating of graphics will reduce symptoms. There is also evidence that most participants adapt after initial VE exposures. However, the study of motion sickness suggests that a small proportion of susceptible individuals never adapt, and evidence from flight simulators suggests that more realistic VEs could be associated with greater symptomatology. This has led Biocca [1992] to conclude that cybersickness is not so much a "bug" that can be eradicated, but more of a "snake in the underbrush" that is there to stay, even though its effects may be reduced. This report discusses the symptoms, dimensions, and hypothesised physiological basis of cybersickness, the factors that cause or affect the severity of symptoms, the phenomena associated with cybersickness, the ways in which it might be prevented or managed, and possible effects of cybersickness on performance.

2. Cybersickness: Side Effects of Virtual Environments

2.1 Characterising Cybersickness

Cybersickness is an unintended psychophysiological response to exposure to the perceptual illusions of VEs. Reported symptoms include stomach awareness, burping, salivation, drowsiness, nausea and occasionally even vomiting, as well as disorientation, dizziness, headaches, difficulty focussing, blurred vision and eyestrain. Symptoms can occur during exposure to the VE and may continue for some time afterwards [Biocca 1992; Cobb, Nichols, Ramsey, & Wilson 1999; Ebenholtz 1992]. The symptoms of gastrointestinal distress and disorientation resemble those usually associated with motion sickness, while the visual symptoms appear to be related more to the visual display [Hettinger & Riccio 1992]. Some have termed the collection of symptoms the Sopite syndrome [Durlach & Mavor 1995], although this may refer principally to the extreme drowsiness that persists even after more marked symptoms have subsided [Kennedy, Lanham, Drexler, Massey, & Lilienthal 1997]. Many have referred to the array of symptoms as simulator sickness by identification with the very similar side effects experienced in flight simulators, while more recently it has been referred to as cybersickness [eg Kennedy, Lanham, et al. 1997]. While discussing VE side effects some authors have also considered other unwanted effects of VEs, including problems resulting from poor ergonomic design and social or ethical issues.

While these issues have been discussed by some authors in the context of VE side effects, they are not considered to be aspects of cybersickness.

Early reports of cybersickness in VEs discussed it in relation to simulator sickness, considering flight simulators to be specific examples of VEs [eg Kennedy, Lane, Lilienthal, Berbaum, & Hettinger 1992]. Simulator sickness was first reported in the 1950s by Havron and Butler, who documented the effects in a Navy helicopter flight trainer [Kennedy, Lanham, et al. 1997]. Since then the phenomenon has been extensively investigated, especially by the U.S. military flight simulator community, and a considerable research literature now exists [see Pausch, Crea, & Conway 1992]. Simulator sickness has in turn been considered in relation to motion sickness, and viewed as resulting from simulated vehicular self-motion. While simulator sickness exhibits a number of motion-sickness-like symptoms and signs, its profile differs from that of true motion sickness. In particular, actual vomiting and retching are rare, while other overt signs such as pallor and sweating are more common, as are the more subjective symptoms described above. Problems considered to be of greatest concern are the after effects, which in the case of flight simulators may extend to illusory sensations of climbing and turning, perceived inversions of the visual field, and disturbed motor control. These symptoms have been sufficiently serious that pilots may be grounded for up to 24 hours following a simulated flight [Kennedy, Hettinger, & Lilienthal 1990].

Symptoms induced by the visual display are particularly prevalent in simulator sickness. These include symptoms not just of eyestrain but also those such as dizziness and nausea. Similar symptoms can be produced in stationary participants viewing from the inside a variety of moving displays, such as rotating striped drums or moving rooms. This phenomenon has been termed visually induced motion sickness (VIMS) [Kennedy, Hettinger, et al. 1990; Pausch et al. 1992]. Unlike the symptoms of true motion sickness, VIMS symptoms may be prevented by closing the eyes [Howarth & Hill 1999]. Attempting to adapt to an altered perceptual environment viewed through reversing, displacing or inverting lenses can cause comparable symptoms, and during adaptation to the altered environment of microgravity in space at least half of all astronauts and cosmonauts have experienced motion-sickness-like symptoms [Crampton 1990]. Kennedy, Frank, and McCauley [1985, cited in Pausch et al. 1992] have suggested that motion sickness, simulator sickness and perceptual adaptation are distinct but overlapping entities.

Not everyone suffers from simulator sickness, or from cybersickness in other VEs. The proportion affected depends on the type of simulator or VE. In a survey of ten U.S. Navy flight simulators, the incidence of sickness varied from 10 to 60% depending on the particular simulator surveyed [Kennedy, Hettinger, et al. 1990]. This wide variation serves to indicate the potentially large effect that the design of a VE could have in either minimising or inducing cybersickness. McCauley and Sharkey [1992] have also pointed out that pilots tend to be less susceptible to these types of symptoms than do the general population, as they are self-selected and subject to attrition based on their resistance to motion sickness. Thus one might expect the incidence of cybersickness in VEs to be much higher as a broader section of the population would participate. Regan and Price [1993a] studied a group of participants, comprised of civilians, military personnel and firefighters, during a 20-minute immersion in a VE generated by an HMD, and then a 10-minute post-immersion period. Of the 146 participants, 61% experienced some symptoms of cybersickness. For 5% of the participants the symptoms were so severe as to cause them to withdraw from the study before the completion of the 20-minute immersion. Other VEs may have greater or lesser symptomatology, given the wide variation in VR systems and the even greater variation in VEs.

In addition to the differing incidence of sickness in different flight simulators, the actual profile of symptoms varies with the simulator studied. Some induce more gastrointestinal symptoms, some induce more symptoms of disorientation, while others induce more eyestrain [Kennedy, Lanham, et al. 1997]. Because this indicates more than one causative factor involved in the varying symptomatology, Kennedy and his coworkers have described simulator sickness as polygenic and polysymptomatic. By means of an enhanced questionnaire method for quantifying simulator sickness, they have identified the three major dimensions of simulator sickness: nausea (eg stomach awareness, increased salivation), oculomotor (eg eyestrain, blurred vision, fatigue), and disorientation (eg dizziness, vertigo) [Kennedy, Lane, Berbaum, & Lilienthal 1993]. These three components of symptomatology are discussed in detail in following sections.

2.2 Theories of the Physiological Basis of Cybersickness

Attempts to understand the physiological basis of simulator sickness have turned to theories of motion sickness, extending the theory to account for symptoms resulting from simulated vehicular self-motion [Kennedy, Hettinger, et al. 1990]. The most widely accepted theory of motion sickness is based on the concept of sensory conflict, which Reason and Brand [1975] developed in detail as their theory of sensory rearrangement. The theory holds that motion sickness occurs in situations where motion cues transmitted to the eyes, the vestibular system and the nonvestibular proprioceptors are at variance with one another, or with what would be expected on the basis of previous experience. The vestibular receptors are crucial to the theory, as individuals without an intact vestibular system do not get motion sickness or other visually induced sickness. The inclusion of conflict with past experience in a similar situation takes account of the fact that most individuals adapt to situations that are initially nauseogenic.

There have been a number of criticisms of sensory conflict theory, and it has become clear that the theory does not fully explain motion sickness, or simulator sickness. For example, it does not account for females having greater susceptibility to motion sickness than males [Reason & Brand 1975], nor does it account for the complexity of the problem, in that the frequency and amplitude of movement (whether real or perceived from a simulation) is often important [Kennedy, Hettinger, et al. 1990]. A number of authors have suggested modifications to the theory. For example, based on experimental evidence some have suggested that the visual and vestibular contribution should be weighted [Eyeson-Annan, Peterken, Brown, & Atchison 1996], while others have suggested that motion sickness could be fully explained in terms of conflict between the sensed and the subjective vertical [Bles, Bos, de Graaf, Groen, & Wertheim 1998; de Graaf, Bles, & Bos 1998].

The strongest criticisms of sensory conflict theory have come from Stoffregen and Riccio [1991], who have argued that sensory conflict per se cannot be responsible for symptoms. In fact sensory conflict is common and generally leads to adaptive changes in the control of behaviour. In contrast, actual motion sickness is uncommon. Thus factors in addition to conflict would be needed to explain motion sickness. While some have proposed additional factors such as conflict thresholds, Riccio and Stoffregen [1991] have proposed an alternative theory. They hypothesise that motion sickness results from prolonged instability of posture, so that symptoms occur in those situations where individuals do not possess or have not yet learned strategies effective for the maintenance of postural stability.

A few studies have attempted to compare and evaluate the sensory conflict and postural instability theories. Studies aimed directly at testing postural control theory have found supporting evidence. For example, Stoffregen and Smart [1998] tested subjects standing stationary within a "moving room" that exposed them to low frequency and magnitude optical flow. In two experiments, the subjects' postural sway increased before the onset of motion sickness symptoms, thus supporting the theory. Owen, Leadbetter, and Yardley [1998] found similar supporting evidence in that for subjects viewing a disorienting virtual reality display, the degree of postural instability was correlated with susceptibility to motion sickness.

However, in a short series of experiments aimed at testing both theories, Warwick-Evans and coworkers have found contradictory results. In the first study, demands on postural control were reduced by having all subjects sit on a hard chair with their heads resting against a restraining device. However, there was no unrestrained comparison group. All subjects watched a film previously taken from the eye-level perspective of someone walking through the university campus. Level of sensory conflict was manipulated by playing the film at either normal speed or speeded up by 20%, with the assumption that the faster perceptual flow of the speeded film would produce greater conflict. All subjects reported motion sickness, suggesting that reducing demands on postural control did not avoid sickness. There was also more sickness associated with viewing the film at normal speed [Warwick-Evans & Beaumont 1991]. While the authors interpreted the latter result as not supporting sensory conflict theory, this conclusion may have missed the subtleties of nauseogenic conflict. Perceived conflict may have been greater with the more realistic display using the normal film speed, and the greater sickness in this condition would then be consistent with the increased incidence of simulator sickness experienced in simulators with increased realism of display [Kennedy, Hettinger, et al. 1990].

Warwick-Evans, Symons, Fitch, and Burrows [1998] addressed some of the shortcomings of the previous study in two further experiments that tested subsidiary hypotheses for both theories: sensory conflict theory predicted greater sickness with greater conflict, and postural control theory predicted reduced sickness with postural restraint. For the first of these experiments, levels of sensory conflict were produced by running the film at either normal or double speed, and levels of postural control by having subjects either standing or lying. In all conditions there was widespread occurrence of motion sickness, again giving general support to sensory conflict theory. The results also gave some limited indication that greater illness resulted from viewing the speeded film. But sickness was found to be significantly greater in the lying than the standing position, which the authors took to be inconsistent with postural instability theory. Because the lying condition may have produced greater sensory conflict, a further study compared film speeds either increased or decreased by 20%, while subjects either stood freely or stood firmly supported by a heavy restraint. Although symptoms were again widespread, supporting the nauseogenic effects of sensory conflict, this time there was no effect of either film speed or postural restraint, giving no support to subsidiary predictions of either theory.

While giving general support to the nauseogenic effects of sensory conflict, and confirming the association of postural instability and sickness, these studies as well as others cited in critiques of sensory conflict theory [see eg Stoffregen & Riccio 1991] indicate that neither theory completely accounts for motion sickness. Despite this, some form of sensory conflict remains the most widely accepted explanation not only of motion sickness, but also of simulator or cybersickness. It is also accepted that postural instability is a feature of simulator or cybersickness. The studies reviewed here also illustrate the difficulties of disentangling and identifying the hypothesised causative factors of sickness. This also becomes an issue when attempting to minimise symptoms in a VE, where careful consideration needs to be given to potential causes of side effects.

None of the foregoing theories account for the visual symptoms reported in both simulator sickness and cybersickness. Some recent studies have investigated these, and these will be discussed in the context of the specifically visual symptoms.

2.3 Adaptation to Altered Environments

A notable feature of all forms of motion sickness is that of adaptation, the diminution and eventual disappearance of the signs and symptoms in most people with continued or repeated exposure [Reason & Brand 1975]. Adaptation has been observed not just to modes of transport, but also with continued exposure to distorting lenses [eg Stratton 1897, cited in Reason & Brand 1975], optokinetic drums that cause VIMS [Hu & Hui 1997], slow rotation rooms [Guedry, Rupert, & Reschke 1998], and weightlessness [Parker & Parker 1990]. Simulation sickness declines with repeated hops in a flight simulator, with adaptation for most trainees complete by the sixth hop [Kennedy, Lane, et al. 1993]. Some adaptation has also been reported as early as the second immersion in a VE displayed via an HMD, suggesting that adaptation in some VEs may occur quite quickly [Regan & Price 1993b].

Cybersickness can be considered as a problem of adaptation to a novel set of environmental cues. However, on leaving the altered environment after effects can occur as a problem of re-adaptation to the normal environment. Studies of simulator sickness have shown there to be a negative relationship between side effects and after effects. Reduced side effects during the simulator hop are usually associated with an increase in after effects, usually manifested as a decrease in nausea during the flight followed by increased postural instability after the flight [Kennedy, Berbaum, & Lilienthal 1997]. Negative after effects of adaptation to VEs have also been reported, again with a decrease in nausea during immersion and an increase in the more insidious symptom of postural instability as an after effect [Stanney & Salvendy 1998].

Among other features of adaptation is that not all individuals adapt. Perhaps as many as 5% of those who are susceptible to motion sickness do not adapt, and motion sickness remains a chronic problem [Reason & Brand 1975]. It would therefore be expected that for a proportion of susceptible VE participants cybersickness could be a continuing problem. Adaptation is also specific to a particular altered environment. Achieving adaptation to one environment does not automatically confer adaptation to another, so that further measures must be taken for each new environment.

2.4 Components of Cybersickness

The unwanted side effects fall into the same three dimensions as simulator sickness: nausea or stomach discomfort, disorientation or postural instability, and oculomotor effects (eyestrain or blurred vision). These dimensions were identified in a series of factor analyses of a large database of results obtained by administering the Pensacola Motion Sickness Questionnaire (MSQ) to pilots following simulator hops. The MSQ was first developed over 30 years ago and until the 1990s was still used to assess various forms of motion and visually induced sickness. The factor analyses also identified items relevant to simulator sickness, and these items now comprise the widely used Simulator Sickness Questionnaire (SSQ) [Kennedy, Lane, et al. 1993].

2.4.1 Nausea

The signs and symptoms grouped under the dimension of nausea are those most commonly associated with true motion sickness. As well as nausea they include pallor, sweating, stomach awareness, burping, increased salivation, difficulty concentrating, fatigue or drowsiness, and general discomfort [Hettinger & Riccio 1992; Kennedy, Lane, et al. 1993]. Actual vomiting or even extreme nausea has rarely been observed in simulators or the VEs studied, but symptoms can be sufficiently severe to cause the participant to withdraw. Although some studies have attempted an objective assessment of this sickness dimension by measuring skin pallor [eg Kennedy, Fowlkes, Berbaum, & Lilienthal 1992], for the most part nausea is subjectively assessed by self-report or questionnaire. Monitoring of physiological correlates of nausea by methods such as electrogastrograms has been used in studying the physiology of motion sickness in the laboratory, but has proven less reliable and too insensitive for prediction of cybersickness symptom severity [DiZio & Lackner 1992].

2.4.2 Postural instability

Postural stability is the ability of an individual to maintain balance and postural control. It relies on input from the visual, somatosensory and vestibular systems. This input is processed and then controls two major reflexes: the vestibular ocular reflex (VOR) that maintains stability of visual objects on the retina, and the vestibular spinal reflex that maintains body postural stability while the individual is in motion. Conflict between the visual and vestibular sensory inputs can cause postural instability (ataxia) as well as motion sickness [Cobb 1999]. Postural instability, manifested as disorientation, dizziness, and unsteadiness in standing or walking, was first reported as an after effect of flight simulator exposure [Kennedy, Berbaum, et al 1997; Kennedy, Fowlkes, & Lilienthal 1993]. For some individuals the symptoms of unsteadiness lasted for hours after exposure [Baltzley, Kennedy, Berbaum, Lilienthal, & Gower 1989]. Postural instability has also been induced by exposure to VEs, although following a short exposure using an HMD the unsteadiness was reported to be short-lived [Cobb & Nichols 1998; Kolasinski & Gilson 1999].

While it is usually assessed as an after effect of exposure, postural instability is also known to occur with motion sickness symptoms. The postural instability theory [Riccio & Stoffregen 1991] predicts that instability actually precedes the onset of symptoms such as nausea. This has been tested in a fixed-base flight simulator, where seated participants were exposed to optical flow that oscillated in the roll axis with frequencies that approximated to spontaneous postural sway during stance. Sway was measured as head motion. Prior to onset of symptoms, those participants who became sick exhibited greater head motion than those who experienced no symptoms [Stoffregen, Hettinger, Haas, Roe, & Smart 2000]. The authors suggest that these frequencies of optical flow could be avoided in displays, so as to minimise side effects.

Postural instability has been measured by a variety of means, subjectively from self-report, and more objectively by a variety of measures. Static posture tests require subjects to hold a fixed stance for a given period, and dynamic tests require subjects to walk along a line, rail, or path. Of these, the static tests using Sharpened Romberg stance, or standing on one leg with eyes closed, have given the most reliable results. Instability is also assessed by sway magnetometry and by video recording of a reticle positioned on the back of a participant's head [Cobb 1999; Cobb & Nichols 1998; Kennedy & Stanney 1996].

2.4.3 Visual side effects

Subjectively reported visual symptoms such as eyestrain, headache, blurred vision, and difficulty in focussing have formed one of the three dimensions of simulator sickness [Kennedy, Lane, et al. 1993]. Studies of side effects of a VE generated by an HMD also reported a high incidence of these symptoms [Regan & Price 1994]. Indications that there could be physiological correlates of these symptoms first came from a report of some helicopter pilots failing a stereoscopic depth perception test following prolonged use of night vision goggles (NVGs) similar in design to HMDs. A subsequent study of the effects of NVG usage showed that contrast sensitivity and depth perception when monocular cues were present did not degrade. However, with prolonged NVG usage there were oculomotor changes that could result in a loss of depth perception relying solely on stereopsis [Sheehy & Wilkinson 1989]. Subsequently Mon-Williams, Wann, and Rushton [1993] found that following a 10-minute exposure to a stereoscopic VR display subjects, participants also showed transient deficits of binocular vision. This finding has since been confirmed by a number of more recent studies [see Howarth 1999]. The results of these studies broadened experimental research into VE side effects from its initial focus on symptoms of gastrointestinal distress and postural instability, to include tests of possible oculomotor changes during VE immersion.

While some oculomotor problems have been reported from the use of non-stereoscopic displays, or even from prolonged viewing of a VDU screen, the displays that remain of most concern are stereoscopic. These displays can potentially stress the mechanisms of binocular vision. Therefore, the principal mechanisms of binocular vision are briefly considered here.

Clear single vision of an object requires both accommodation and vergence to operate. The process of accommodation, in which the eyes focus on near objects and relax focus for distant objects, is driven by image blur. The primary goal of accommodation is to minimise the blur. The vergence system operates to produce a single perceived image from the two retinal images, by bringing the images close to the fovea of each eye so that they can be fused into a percept of a single object at a given depth. During this process the eyes converge upon near objects and diverge to fixate upon far objects. The accommodation and vergence systems interact via neural cross-links, so that a response in one system drives a corresponding response in the other. While it is known that the cross-links are open to adaptive change the process and limits of adaptation are not fully understood [Rushton & Riddell 1999; Wann & Mon-Williams 1997].

Problems of stress on the visual system have been most obvious in HMDs. While poor engineering design or incorrect calibration for the user can be a source of visual stress, a problem less easy to avoid is the challenge to the accommodation-vergence cross-links. Current stereoscopic VR displays provide an illusion of depth by providing each eye with a separate 2D image on a fixed focal plane. The mechanisms of binocular vision fuse the images to give the 3D illusion. Because there is no image blur, the eyes must make a constant accommodative effort. But at the same time the images stimulate a changing vergence angle with changes in apparent depth, so that the normal cross-linked relationship between the systems is disrupted [Mon-Williams & Wann 1998]. The problem is not limited to HMDs as any stereoscopic display, from a stereoscopic desktop to immersive systems such as the CAVE, uses the same display method [Wann & Mon-Williams 1997]. Within certain limits the visual system can adapt, as shown by results of orthoptic exercises and of adaptation to different prisms placed in front of each eye. However, whether the changes are long term or whether there can be dual adaptation to both the real and virtual environments has not been established [Rushton & Riddell 1999].

What has been shown in several studies is that short-term exposure to VEs with stereoscopic displays has produced changes in heterophoria (latent squint), where the visual axes of the eyes deviate from their usual position. The resting vergence angle of the eyes may be altered either in the direction of exophoria (turning outwards of the eyes) or esophoria (turning inwards of the eyes). Some decrements in visual acuity have also been reported. These objective changes, which must be assessed using orthoptic instruments, are associated with reports of subjective symptoms such as blurred vision, headaches, eyestrain or momentary diplopia (double vision). The degree of objective change and the symptomatology also depended upon the VR system or VE being evaluated [Costello & Howarth 1996; Mon-Williams & Wann 1998; Mon-Williams et al. 1993]. The reported changes in heterophoria could account at least in part for the subjective symptoms as well as reduced visual acuity and reduced perception of depth when relying on stereopsis. These changes are similar to those reported with the use of NVGs and thought responsible for the reduced depth perception [Sheehy & Wilkinson 1989]. While the observed changes associated with VE exposure have usually been short-lived, it should be noted that the actual time spent immersed in the VE was short (often only 10 to 20 minutes). Whether longer exposure times produce greater or longer-lasting changes is still unknown. Certainly longer exposures in flight simulators result in greater severity of symptoms overall [Kennedy, Stanney, & Dunlap 2000].

Some researchers have assumed that all problems of visual stress may be avoided by use of a well-designed and suitably calibrated biocular display. While a biocular display still gives mismatched cues for accommodation and vergence, the bias remains constant [Mon-Williams & Wann 1998]. However, there is still disagreement in the literature over the possible effects of biocular displays [Rushton & Riddell 1999]. Some factors that have been shown to cause greater oculomotor changes are inappropriate vertical gaze angle [Mon-Williams, Plooy, Burgess-Limerick, & Wann 1998], carrying out a prolonged object handling task in a VE [Kawara, Ohmi, & Yoshizawa 1996], and visually tracking an object oscillating from virtual infinity to near [Mon-Williams & Wann 1998]. These results indicate that improvements in VR technology alone may not solve the problem of visual stress, but that attention to characteristics of the VE and of the required task may avoid some of the oculomotor changes. In particular, monocular depth cues such as relative size and height of objects, overlap, texture gradients, convergence of parallel lines, and motion parallax, should be provided in a VE if stereoscopic vision is affected. The task should also be tailored to avoid unnecessary stress on the visual system.

2.5 After Effects

Symptoms of cybersickness are not necessarily limited to the time of actual VE immersion. Gastrointestinal symptoms may subside only gradually upon leaving the VE. Other symptoms experienced following immersion may include adverse changes in binocular function (heterophoria, reduced visual acuity, or subjective symptoms of eyestrain), disturbed locomotor and postural control, perceptual-motor disturbances, and insidious effects such as drowsiness or fatigue [Kennedy & Stanney 1996; Mon-Williams et al. 1993; Stanney & Salvendy 1998]. Proprioceptive after effects have been reported, with consistent changes in both pointing direction and felt limb position [Stanney, Kennedy, Drexler, & Harm 1999]. The possibility of transfer of maladaptive cognitive after effects to the real world has also been suggested. All these after effects are of some concern, as they raise issues of the safety of both the participants and others. Possible adverse consequences include those that are individual, social, legal, and economic [Kennedy & Stanney 1996]. An unfortunate feature of after effects is their reciprocal nature with sickness during the actual immersion. Those participants who have fewer and less severe symptoms during VE immersion frequently experience more pronounced after affects [Kennedy & Stanney 1996].

Although existing evidence from relatively brief immersions in a VE suggests that the subsequent measurable oculomotor changes may be quite short-lived, it is not clear whether longer immersions would have longer-lasting effects, or whether some susceptible individuals may have greater oculomotor problems. At present the after effects of greatest concern are those of postural instability and disorientation. Evidence from studies of simulator and motion sickness suggests that these effects may persist for some time following immersion. In a study of the time course of simulator sickness symptoms following a simulator hop, Baltzley et al. (1989) found symptoms in 45% of the more than 700 pilots tested. As well as symptoms of nausea and eyestrain, pilots reported dizziness, vertigo, problems with walking straight, and the perceptual problems of distorted sense of speed and illusions of movement. For 25% of the pilots, their symptoms lasted for more than an hour post hop, and 8% reported symptoms lasting for more than six hours. Studies of the time course of symptoms of motion sickness also indicate possible delayed recovery. Of additional concern is that subjective recovery may be much more rapid than objective recovery. Subjects in whom motion sickness was induced by sitting in a chair on a rotating turntable reported that within one hour they had subjectively recovered, as assessed by absence of subjective symptoms. However, objective recovery as assessed by susceptibility at re-challenge on the turntable took considerably longer, indicating that subjects remained sensitised to subsequent motion for up to two hours, twice the length of subjective recovery. Thus individuals who experience symptoms may not be able to give an accurate subjective judgement of their vulnerability following exposure

[Golding & Stott 1997]. The time course of recovery from after effects of VE exposure remains to be investigated.

3. Factors Causing or Affecting Sickness

Most discussions of factors either causing or influencing the degree of cybersickness have differentiated between three groups of factors: those factors associated with the individual, those associated with the VR/VE system, and those associated with the task to be performed in the VE [Biocca 1992; Kolasinski 1995]. Identification of the factors associated with the individual user of the VR/VE system is of use in determining those most at risk, and can be used to screen those most susceptible. It has frequently been assumed that the factors associated with the system and the task will either be eliminated or at least minimised as the technology improves. However, technological improvements would be expected to improve the realism of the experienced VE and so in some cases may actually increase rather than decrease the incidence and severity of symptoms [Kennedy et al. 2000]. The majority of the attention in this area so far has focussed on the dimensions of nausea and postural instability, drawing heavily on the motion sickness and simulator sickness research literature. Only recently as visual symptoms have been reported with HMDs has attention been given to the oculomotor symptoms.

3.1 Factors Associated with the Individual

Individuals differ in their susceptibility to cybersickness. Factors that have been shown to influence susceptibility to motion sickness, simulator or cybersickness include age, gender, ethnicity, spontaneous postural sway, flicker fusion frequency threshold, plasticity or adaptability, and previous experience with either the real world or simulated task. Perceptual and cognitive characteristics such as field dependence/independence and mental rotation ability are believed to have an influence on susceptibility, as are state variables such as fatigue or illness. People with visual deficits may be more susceptible to oculomotor side effects, although this has yet to be verified experimentally. A past history of motion sickness has been found to predict susceptibility to sickness in a variety of circumstances, including during immersion in a VE.

Studies of motion sickness have found both age and gender to influence the incidence of symptoms. Motion sickness susceptibility has been found to be almost non-existent among the very young, to be greatest between the ages of 2 and 12, and to decrease rapidly after 12 years of age. By the age of 25 it has dropped to about half that observed between the ages of 17 and 19. After 25 years it decreases more slowly, and after the age of 50 motion sickness is rare [Mirabile 1990; Park 1998; Reason & Brand 1975]. Females have consistently been found to be more susceptible than males to motion sickness [Mirabile 1990; Reason & Brand 1975; Turner & Griffin 1999]. Because most incidence studies rely on self-report, earlier researchers had speculated that females might report rather than experience more symptoms, but there is some evidence of hormonal influences on motion sickness susceptibility [Mirabile 1990].

Some studies have shown ethnicity to influence susceptibility, with Asiatic peoples being more susceptible. Stern, Hu, LeBlanc, and Koch [1993] found Chinese to be more susceptible than European-Americans or African-Americans on both subjective and objective measures to motion sickness induced by a circular vection drum. Sharma and Aparna [1997] found Tibetans and Northeast Indians to report greater susceptibility than Caucasian races, suggesting a genetic component. Because motion sickness susceptibility is predictive of sickness in a wide range of provocative situations, it would be expected that similar underlying factors be involved in the overall susceptibility. For example, past history of motion sickness is predictive of airsickness, seasickness, sickness induced by vertical acceleration or rotation chairs, VIMS induced by rotary visual fields, simulator sickness, and side effects of nausea and vomiting from cancer chemotherapy [Golding 1998; Hu, Glaser, Hoffman, Stanton, & Gruber 1996; Kennedy, Fowlkes, et al. 1992; Morrow 1985]. Thus individual difference factors influencing motion sickness susceptibility could reasonably be considered as factors influencing susceptibility to the gastrointestinal symptoms and possibly the postural instability of cybersickness.

While postural instability is itself one of the dimensions of cybersickness and is frequently associated with the gastrointestinal symptoms of motion sickness, there is also evidence that an individual's baseline postural stability may be inversely associated with susceptibility to motion sickness or cybersickness. In testing the postural instability theory of motion sickness causation, Stoffregen and Smart [1998] looked at spontaneous body sway before and during exposure to a moving room. Not only did they find that an increase in postural instability preceded the onset of motion sickness symptoms, but those subjects who developed motion sickness showed greater spontaneous sway before exposure. This suggests that reduced postural stability while unchallenged may be related to sickness susceptibility. Those who are susceptible to sickness may also develop instability more readily, as Owen et al. [1998] found a self-reported history of motion sickness to be related to degree of body sway produced by viewing a disorienting VR display.

A number of other individual characteristics have been found to be associated with motion sickness susceptibility. Flicker of the display can induce symptoms in flight simulators [Pausch et al. 1992]. While flicker is usually considered only a technical problem, it also relates to a characteristic of the user. Individuals differ markedly in their flicker fusion frequency threshold, the point at which flicker becomes visually perceptible [Kolasinski 1995], so that those with a lower threshold would be more vulnerable to visual and other symptoms. Individuals also differ in plasticity, or their ability to habituate or adapt, with some adapting much more readily to repeated exposures to a stimulus. It has been suggested that those with greater plasticity will be much less susceptible to motion sickness or cybersickness symptoms, although the implied time course may mean that greater plasticity is associated with faster symptom reduction on repeated exposures, rather than fewer initial symptoms [Kennedy, Dunlap, & Fowlkes 1990].

Little attention has so far been given to whether some individuals may be at greater risk of developing oculomotor symptoms following exposure to VEs. It has been established that changes in heterophoria and visual acuity can occur after a relatively brief immersion, and transient myopia may be produced by an accommodation spasm [Howarth 1999]. To date, most concern has been over the use of VR systems by children, as the immature visual system may be more susceptible to developing abnormalities that can lead to visual problems such as strabismus [Rushton & Riddell 1999]. It could reasonably be expected that individuals with poorer binocular function would experience more oculomotor side effects than individuals with normal vision. It may also be the case that time to recover from the transient heterophoria varies between individuals. Because attention to the physiological oculomotor changes has been so recent, no studies to date have investigated the issue of who is most at risk. Also, there have been no investigations carried out on the oculomotor effects of prolonged VE exposure.

Perceptual and cognitive characteristics appear to influence susceptibility to motion sickness or cybersickness. Field dependence/independence is a perceptual or cognitive style that determines the degree to which the surrounding field influences an individual's perception of an object within that field. The most common test of field dependence is the rod and frame test (RFT), in which subjects must align a rod to the true vertical while it is within a frame that can be tilted to create visual conflict. Field dependent subjects judge the vertical as deviated in the direction of the misleading tilted frame, while field independent subjects make more accurate judgements of the true vertical. A considerable amount of research has related field dependence/independence to aspects of interpersonal behaviour. Field dependent individuals are said to be more attentive to social cues, more interested in others, and more influenced by external social referents that help them to minimise ambiguities. The field dependence/independence dimension is seen as bipolar, with those at the extremes of the dimension showing cognitive styles that are adaptive in different situations [Witkin & Goodenough 1977]. Several studies have examined the relationship between field dependence and simulator sickness, with the prediction that field independent individuals would be less susceptible. The early findings of Barrett and Thornton [1968] showed a complex relationship, but gave some indication that the field independent subjects were in fact more affected by simulator sickness. Other studies have produced sometimes-conflicting results, although most evidence now suggests that individuals highly susceptible to motion or simulator sickness are intermediate between the extremes of field dependence/independence. It is possible that the two perceptual styles are associated with different strategies to adapt to the sensory conflict, while those without a strong strategy succumb [Mirabile 1990].

Another cognitive characteristic that can affect cybersickness susceptibility is mental rotation ability. Observers can more readily recognise shapes and objects presented in unusual orientations if they are able to rotate the object mentally. This would suggest that individuals would adapt more readily to the stimulus rearrangement of a VE, and possibly suffer fewer symptoms, if they were adept at mental rotation. Parker and Harm [1992] studied astronauts in the altered environment of microgravity either on space missions or in a simulator, and found that astronauts with better mental rotation abilities were less susceptible to space sickness. Further, astronauts could be trained in mental rotation ability prior to and during a space flight, and were then less susceptible to space sickness. This suggests that mental rotation ability training prior to VE immersion might avoid or reduce cybersickness, although no studies to date have tested this.

Experience or training in either a simulator or the real world task being simulated is implicated in susceptibility to simulator sickness. It has been a consistent finding that experienced air crew suffer a higher incidence of simulator sickness symptoms than do less experienced crew. This has been assumed to be due to the greater experience with the sensory conditions of actual flight making the experienced pilots more sensitive to discrepancies experienced in the simulator [Kennedy, Hettinger, et al. 1990]. In contrast, greater experience with the simulator usually causes fewer symptoms, due to adaptation. Adaptation to VEs is discussed in a later section.

State variables can have an effect on cybersickness susceptibility. Illness may increase an individual's susceptibility. In fact, anyone suffering from fatigue, sleep loss, head colds or any respiratory illness, ear infections, hangover, upset stomach, or emotional stress may be more susceptible than when in their normal state of health. Use of alcohol or even some medications, or having received a recent immunisation, can increase susceptibility [McCauley & Sharkey 1992; Pausch et al. 1992]. Although it was a popular belief that anxiety or an anxious disposition predisposed to motion sickness, tests of the relationship between anxiety and various forms of motion sickness have provided little support, so it must be assumed that any effect would be small [Kennedy, Dunlap, et al. 1990]. Regan and Price [1993a] observed that levels of concentration may affect the severity of cybersickness, with greater degree of concentration associated with lower levels of sickness. This anecdotal observation still needs to be verified experimentally, but may provide a means of coping with mild symptoms. Two other factors associated with increased cybersickness symptomatology are the subjective experience of vection [Hettinger, Berbaum, Kennedy, Dunlap, & Nolan 1990] and the subjective sense of presence [Stanney & Salvendy 1998]. Both of these factors are discussed in a later section.

Biocca [1992] points out that the question, "Who is susceptible to simulation sickness?", has two implied parts. It asks both who is likely to experience some discomfort, and who is likely to be most affected by the symptoms. In general, studies of individual susceptibility have not explicitly differentiated between two such groups, and a continuum of susceptibility has been tacitly assumed. A further complication is that some individuals will be more susceptible to some symptoms, for example oculomotor symptoms, while others may experience different symptoms such as nausea or instability. The foregoing discussion suggests those individual characteristics that may contribute to susceptibility, and indicates conditions in which more symptoms might be expected. However, Kennedy et al. [2000] point out that theoretical treatments of individual difference and system factors have failed to produce a good predictive model, and speculate that the factors may account for only a small proportion of the total variance. In contrast, they believe that temporal factors such as exposure duration and number of repeated exposures could account for 20% to 50% of the variance in cybersickness susceptibility. This is an encouraging proposition, as it suggests that many cybersickness symptoms can be managed with appropriate attention to procedures.

3.2 Factors Associated with the VR System

Some factors associated with the VR systems used, and the VEs generated, can induce cybersickness. These include poor calibration and lags resulting from transport delay or update rate. Other factors are refresh rate, flicker, the realism of the display, and spatial properties such as field-of-view and viewing region. Some features of HMDs designed for binocular viewing may also cause problems.

While some cybersickness symptoms may still occur in susceptible individuals even in well-engineered systems, poor engineering or calibration of a VR system can certainly exacerbate the symptoms or even be their sole cause. Indeed, any factor that increases the sensory conflict for users can potentially increase symptoms. It is important that these technological factors be identified, as they are the factors most amenable to technological solutions. Regardless of how well it is engineered, for any VR system it is important that the alignment, size, and focus of the optical display be properly calibrated to minimise symptoms, a practice routinely carried out in flight simulators [McCauley & Sharkey 1992].

Lags in the visual display can be a cause of cue conflict and consequent cybersickness. Time lag from transport delay, the time period from input to the completion of the first field of video output, could potentially affect both performance and cybersickness symptoms. Most studies have looked at performance in flight simulators, where longer lags have a greater effect in degrading performance. Yet while transport delays could give misleading motion cues and thus cause sickness, studies done in simulators have found no effect [Kennedy, Hettinger, et al. 1990; Pausch et al. 1992]. In systems with position tracking, real time measurements of the position and orientation of the user are passed to the VR system and used to control computer-generated stimuli in the VE. Because it is then the key system for coupling the user's head, vision, and sometimes hands or body, to the VE, errors in position tracking can lead to visual-proprioceptive conflicts. While it has not caused sickness in simulator studies, delayed feedback from head or body position trackers can delay adaptation and may cause sickness in VEs. Possibly more disruptive is error that causes differences between "felt" and "seen" limb positions, particularly as the error from some trackers is not constant. Jitter or oscillation of represented body parts can also cause symptoms of nausea if the oscillations are in the range of 0.2 to 0.25 Hz [Biocca 1992].

Update rate refers to the speed at which successive frames of a moving scene can be generated and rendered into the frame buffer ready for display. The update rate is determined by computational speed, but can vary dramatically depending on the complexity of the scene. As a consequence there may be trade-offs between complexity of the scene displayed and realistic representation of motion. In an HMD, if a scene is updated at a rate above 12 Hz the motion is perceived as smooth, and motion parallax cues support depth perception. However, updates provided at a slower rate than 12 Hz may give cues of illusory motion and induce symptoms of cybersickness [Piantanida, Boman, & Gille 1993].

Refresh rate, referred to by some authors as frame rate, indicates how often the frame buffer is examined and displayed onto the screen, and the rate is essentially determined by the system hardware. Refresh rate is related to the problem of flicker, in that slower refresh rates promote flicker that can cause cybersickness symptoms of both nausea and eyestrain. Flicker above 30 Hz is usually not detectable in human foveal (or central) vision, but may be detected in peripheral vision [Pausch et al. 1992]. Also, as discussed above, individuals differ in their flicker fusion frequency threshold. Flicker is also related to the luminance, or brightness, of the display, with flicker increasing as the brightness increases. In current VR displays, luminance is typically set to avoid flicker above 30 Hz. Because see-through displays often require higher lighting levels, and there may be limited control of real world lighting, higher refresh rates are often needed for augmented reality displays [Durlach & Mavor 1995]. Flight simulators with slower refresh rates often reduce the display luminance and operate in dusk conditions to avoid flicker. Slower refresh rates with CRT displays need more persistent phosphors. Because these will continue to glow as the scene is refreshed, the phosphor lag causes a smearing effect and makes them unsuitable for faster moving images [Pausch et al. 1992]. Also related to luminance are contrast, the ratio of the highest to lowest luminance, and resolution, the level of detail provided by the display. Adjustment in one of these parameters may require adjustment of the other two to maintain a good visual display. The resulting display quality may be important in avoiding visual symptoms. While the colour properties of a display may affect performance in selected tasks, no effect has been shown on possible cybersickness [Pausch et al. 1992].

Spatial properties of the display may be implicated in producing cybersickness symptoms. A number of studies have examined field-of-view in simulators, with most results indicating that wider field-of-view displays enhance performance but increase the likelihood of simulator sickness. The incidence of sickness depends upon the task performed. A wide field-of-view display gives greater stimulation and a more compelling simulation of motion that can induce stronger vection, the perception of self-motion. Since vection is related to cybersickness symptoms (see section below), this was assumed to be the reason that a wide display was more likely to cause nausea than one with a restricted field-of-view [Pausch et al. 1992]. However by using a moving scene of randomly positioned dots, Anderson and Braunstein [1985] were able to induce vection using a narrow field-of-view display with a visual angle of only 7.5° in the central visual field. They concluded that motion and texture could be stronger determinants of vection than field-of-view. This would suggest that sickness could be produced by apparent rapid self-motion even in a narrow field-of-view display. A wide field-of-view display may however increase the risk of cybersickness by increasing the likelihood that flicker will be perceived. Flicker is more readily perceived in peripheral than foveal vision, so that characteristics such as refresh rate and luminance that give an acceptable display for a narrow field-of-view may cause symptoms with a wide field-of-view [Kolasinski 1995].

Another spatial property that needs consideration is the viewing region, the volume in front of the display from where the observer can see a clear and undistorted view of the simulated scene. At the centre of this volume is the design eyepoint, the optimal position for viewing the display. As the viewer moves further away from the design eyepoint the image will become progressively more distorted, and when the viewer moves completely outside the viewing region the image becomes either unacceptable in quality or disappears altogether. Viewing a moving display from positions too far from the design eyepoint could be expected to increase the risk of various cybersickness symptoms. In certain flight simulators, aircrew positioned away from the design eyepoint experienced considerably increased symptoms [Kennedy, Hettinger, et al. 1990; Pausch et al. 1992]. It could also be expected that the distorted visuals outside the viewing region could increase the risk of visual symptoms. The adverse effects of the optical distortions would be greater with highly detailed imagery in which the irregularities would be more noticeable, and wide field-of-view displays may also magnify the effects by providing inappropriate motion cues to peripheral vision [Kennedy, Hettinger, et al. 1990].

Attempts to find engineering solutions to the problem of sickness in flight simulators have not so far been successful. It was initially believed that including a motion base in the simulator design would both enhance training effectiveness and reduce the incidence of simulator sickness by reducing the disparities between the visual and vestibular motion cues. However, not only is there limited support for the enhanced transfer of training, but simulator sickness still occurs frequently in moving base systems. This has been attributed to the inability of the motion base to produce motion cues of sufficient fidelity, particularly as the manoeuvres become more aggressive [McCauley & Sharkey 1992]. Kennedy, Hettinger, et al. [1990] have observed that increased realism in simulators is frequently associated with an increase rather than a decrease in simulator sickness. These findings have particular relevance for the more immersive VEs employing head-tracking and wide field-of-view displays.

The problems associated with binocular viewing of stereoscopic displays have been discussed above in the section on visual side effects. Some properties of VR systems may exacerbate these problems. Early HMD displays were not well engineered, and frequently used low resolution LCD screens placed close to the eyes, providing images with poor contrast and illumination. These displays could cause visual symptoms and frequently did so [Wann & Mon-Williams 1997]. In a study of one possible system-induced problem, Regan and Price [1993c] measured the inter-pupillary distance (IPD) of subjects who had completed a 20-minute immersion in an HMD-generated VE. They had predicted that subjects who verbally reported ocular related problems would be those with the greatest IPD deviations from the fixed system configuration. Instead they found this to be confirmed only for the subjects with IPD less than the system configuration. Howarth [1999] refuted this finding both theoretically and empirically, and concluded that a mismatch between the subject's IPD and the system inter-ocular distance (IOD, distance between the centres of the system lenses) caused no increase in symptoms. But based on both theoretical considerations and empirical findings from studying the same group of subjects using different HMD systems, he asserted that a mismatch between the system IOD and inter-screen distance (ISD) was of far greater concern. The effects of this mismatch have yet to be investigated empirically.

While some investigations have been carried out on HMDs, there are no studies currently in the literature of the oculomotor effects of screen-based stereoscopic displays. It could reasonably be expected that there might be changes in heterophoria following exposure to a VE stereoscopically displayed on a wide screen, but neither this nor the effects of the system calibration for effective ocular separation have yet been examined.

3.3 Factors Associated with the Task

Features associated with the task to be carried out in the VE may influence the likelihood of cybersickness. The most important of these is the duration of exposure to the VE. Other factors include cues of self-movement given by global visual flow, which is affected in a fly-through task by altitude, rate of acceleration, and type of manoeuvre, each of which may induce vection and possibly sickness. Head movements during simulated movement have been shown to induce sickness. Body posture and stability may have an effect on symptoms. The participant's degree of control over movement in the VE, and method of movement through it, are also potential influences on sickness. Each of these factors needs to be considered when designing the task for the VE.

Duration of exposure is rated by Kennedy et al. [2000] as one of the two most important factors in determining the incidence of cybersickness, the other factor being number of repeated exposures. The latter determines adaptation, and is discussed below. Evidence from a number of related areas has shown that the longer the exposure, the greater the incidence of sickness. Miller and Graybiel [1970] showed that longer exposures resulted in greater motion sickness produced by rotation. Many studies have shown that more symptoms of simulator sickness occur with longer simulator hops. This has led to recommendations that simulator flights be limited to no more than two hours, and that breaks or time-outs be scheduled when longer training sessions are needed [Kennedy, Hettinger, et al. 1990]. Cybersickness symptoms increase with the length of time spent in a VE. Regan and Price [1994] found that the subjective ratings of sickness increased steadily with time during a 20-minute immersion in an HMD-generated VE. Lampton et al. [1994] also found that the longer the exposure duration, the more severe the cybersickness symptoms became over a 40-minute exposure period. Thus when designing a task to be performed in a VE, careful consideration must be taken to the time involved.

The likelihood of cybersickness symptoms is influenced by a number of factors related to cues of self-movement through the VE. The global visual flow, the rate at which objects flow through the visual scene, has been shown to influence sickness, with greater sickness resulting from faster rates of flow [McCauley & Sharkey 1992]. This has implications for a number of features of the task performed in the VE. For example, in a fly-through the altitude above the terrain is related to visual flow, so at low altitudes where the terrain features are moving rapidly there is a greater risk of illness. This is confirmed by flight simulator studies, which have also led to recommendations both for manoeuvres and for management procedures in simulators. These include avoidance of rapid gain or loss of altitude, high rates of acceleration, unusual or aggressive manoeuvres, abrupt freezing of the display, and abrupt changing of observer position while the visual display is on. Each of these has the potential to induce sickness [Kennedy, Hettinger, et al. 1990; McCauley & Sharkey 1992]. All movement cues can induce vection in susceptible individuals, and vection is strongly associated with cybersickness [Hettinger, Berbaum, et al. 1990].

Factors relating to the body position adopted or actual body movement during VE immersion can influence sickness. One type of movement that is particularly provocative of sickness, during either actual or simulated motion, is head movement. Making head movements during passive rotation of the body is extremely nauseogenic. Tilting the head out of the axis of body rotation generates Coriolis and cross-coupling stimulation of the otolith organs and the inner ear semicircular canals, which are sensitive to angular acceleration, and also generates Coriolis acceleration of the head. Known as the Coriolis effect, the result is a complex pattern of activation that is both confusing and difficult to resolve perceptually, so that the resulting conflict is highly provocative of symptoms [Lackner 1993]. For example, head movements made in a moving and turning vehicle have long been known to induce motion sickness symptoms [Reason & Brand 1975].

Head movements made in the presence of only visual cues of self-motion are also nauseogenic. This has been termed the pseudo-Coriolis effect [Dichgans & Brandt 1973]. As an example, simulator sickness can be induced or exacerbated by head movements made during manoeuvres [Kennedy, Hettinger, et al. 1990]. Wearing prism spectacles that reverse or invert objects in the visual field can give apparent cues of self-motion when moving the head, and can also elicit motion sickness symptoms [Gonshor & Melville Jones 1976]. Cobb et al. [1999] also observed that subjects adapted their physical behaviour to reduce discomfort, and in particular they minimised rotational head and body movements. Thus it might be expected that head movements made during immersion in a VE providing strong self-motion cues would be nauseogenic. The problem could be greater for HMD-generated VEs, as DiZio and Lackner [1992] have pointed out that the effective weight of the head is an aetiological factor for sickness. They report studies that have shown subjects wearing weighted helmets to experience more severe motion sickness symptoms.

Regan and Price [1993d] addressed the issue of head movements in HMD-generated VEs by comparing the reported symptoms of two groups of subjects over a 10-minute immersion period. One group of subjects engaged in pronounced head movements and rapid interaction with the VE, while the other group was free to keep their head movements and interaction speed to a comfortable level. After five minutes the group who made more head movements showed more symptoms, a difference that was significant at the 10% level. After ten minutes in the VE there was no significant difference between the groups, although there was a non-significant trend towards the head movement group experiencing more symptoms. This gives some limited support to the prediction that head movements made while moving through a VE can be nauseogenic.

Results of motion sickness studies suggest that body position and the degree of postural restraint may affect the incidence of cybersickness. Reason and Brand [1975] noted a significant reduction in motion sickness symptoms when individuals lay down, which they attributed to decreased motion of the head. The postural instability theory of motion sickness [Riccio & Stoffregen 1991] would also predict greater incidence of motion sickness in individuals who had less postural stability or restraint. Stoffregen et al. [2000] did find that subjects who developed symptoms of simulator sickness first showed greater instability (as measured by head motion) than those who did not. However, while the studies of Warwick-Evans and coworkers failed to confirm the prediction that bodily restraint would prevent symptoms of visually induced motion sickness [Warwick-Evans & Beaumont 1991; Warwick-Evans et al. 1998], as was discussed earlier these studies did have some methodological problems. Regan and Price [1993d] compared the effects of sitting versus standing while using a 3D mouse to move through a VE. They reasoned that because subjects made small movements while standing, this could either lead to greater conflict and thus increase side effects, or provide additional kinaesthetic and vestibular cues that could attenuate side effects. Equally, sitting could be seen as providing more postural restraint. However, their results showed no difference between the sitting and the standing groups. The results of the few studies done to date give little support to the benefits of postural restraint, so it is not clear whether postural instability can be avoided by use of such restraints. Whether they are beneficial in preventing symptoms may depend on the type of task and other factors that predispose to cybersickness, and this remains to be tested. Because postural instability can occur in VEs, it would be reasonable to recommend that where possible participants be seated while viewing moving displays, particularly those with high rates of visual flow. Also, because head movements during apparent self-movement are so nauseogenic, head rests would be similarly advised in those conditions.

The degree of control that a participant has over movement in a VE may influence susceptibility to cybersickness symptoms. This is comparable to the phenomenon of drivers being less susceptible to motion sickness than passengers. The incidence of simulator sickness is lower among pilots than it is among co-pilots or other crewmembers, and it is pilots who usually have the greatest control over the visual display and any movement [Pausch et al. 1992]. Lackner [1990] also found that subjects who generated input themselves were less susceptible to sickness. Greater degree of control helps the individual to anticipate the actual or simulated movement, possibly also aiding postural stability.

Stanney and Hash [1998] compared the effects of different types of control in reducing the incidence of cybersickness experienced while navigating through a VE generated by a stereoscopic desktop display. An active control group used a joystick to manoeuvre in all directions. This group of subjects could control movement forward and backward, side to side, up and down, as well as roll, pitch and yaw. A passive group was required merely to observe scripted scenes showing continual movement. A third group (the active-passive group) could use a limited set of movements. These were forward and backward, side-to-side, and yaw, and in only selected tasks that required the movement could they use up and down, or pitch movement. The active control group experienced less severe symptoms than the passive group with no control over their movements, but the active-passive group experienced even less sickness. It was suggested that the multitude of movements available to the active control group made control of movement more difficult and complex, leading to a higher level of conflicting sensory cues than for the active-passive group. For the latter group, control of movement was simpler and more streamlined, and adaptation to the VE could have been faster. This suggestion needs further investigation.

The method of movement through a VE can affect the amount of cybersickness symptomatology. Regan and Ramsey [1994] compared two types of movement through an immersive VE generated by an HMD. One group of participants sat on chairs throughout, and controlled their movement through the VE with a conventional 3D mouse. The other group used an exercise bicycle modified so that forward pedal movement produced movement through the VE and the position of the bike handlebars controlled the direction. They reasoned that movement using the bike would produce less sensory conflict as the vestibular and kinaesthetic cues to body position and movement would be more in alignment with the visual cues. Thus use of the bike should reduce cybersickness symptoms. Contrary to predictions, the bike group showed both a higher incidence of symptoms and more severe symptoms. The bike group also performed significantly worse on the experimental task, although this could have been because riding the exercise bike made the task more cumbersome. The authors reasoned that use of the exercise bike had not removed sensory conflict, as the condition provided none of the vestibular cues that a bike rider would use for balance and orientation in the real world. However, it could also be argued that use of the bike produced a more realistic VE, and the subtler sensory mismatch was harder to resolve.

Chance et al. [1998] compared the effects of three different modes of locomotion through an immersive VE consisting of a virtual maze with objects placed at key locations throughout. In the Walk mode, subjects walked normally in the experimental room while tracking of body position and heading were used to update the visual imagery. In the Visual Turn mode, subjects moved through the VE using only a joystick, so that the only sensory cues were provided by the visual imagery. In the Real Turn mode, subjects physically turned in place to steer while they were translated passively through the VE. This mode gave only visual cues of translation but included proprioceptive and vestibular cues for rotation, and so was midway between the other two modes. All subjects traversed a virtual maze in each of the three modes. Mode of locomotion had a significant effect on the degree of cybersickness, with the lowest incidence in the Walk mode and the highest in the Visual Turn mode that provided no proprioceptive cues. Performance on a directional estimate task followed the same pattern, suggesting that subjects should be allowed to explore VEs using real rotations and translation wherever possible. This study gave clear support to the proposition that degree of control influences the amount of cybersickness experienced.

Howarth and Finch [1999] compared two strategies differing in the amount of head movement required for exploring a VE generated by an HMD. The VE was a game, in which subjects moved through a virtual world while shooting monsters, so that constant changes of direction and view were needed. The same group of subjects completed trials using each strategy while seated on a non-rotating stool to avoid increased instability, and for each strategy movement forward and backward was accomplished using a hand-control. In the first condition, subjects used only the hand control to change direction and consequent view of the VE, while in the second condition they changed their direction and view by moving their heads. In this condition they were encouraged to move about actively in the VE. The head movement strategy involved an appreciable update lag following head movement, thus introducing additional sensory conflict due to greater mismatch between visual and vestibular cues. In accordance with predictions, nausea increased across a 20-minute immersion in each of the two conditions, but nausea was much greater in the head movement condition. This result is in accord with other studies showing greater sickness with longer duration exposures, and with the findings of update lags causing increased sickness. It is also consistent with predictions of a nauseogenic effect of head movements in a moving VE.

The visual aspects of a task performed in a VE can influence the incidence of oculomotor symptoms. Mon-Williams and Wann [1998] used VEs generated on a stereoscopic desktop display to compare the effects of four different visual tasks on binocular vision. The tasks differed in the demands they made upon the binocular function of the participants. The study used four groups of participants with full binocular vision, good stereopsis, and normal amplitudes of accommodation and convergence. The first group was shown a bi-ocular display consisting of a set of anatomy photographs, and participants were required to identify a series of anatomical features. The second group viewed the same set of photographs stereoscopically, with disparities set to provide a compelling sense of depth, although the maximum virtual distance between near and far objects remained within the range of 5 to 10 cm, thus making relatively small demands on the vergence system. The third group took part in a game task that required them to scan and attend to display detail, as they had to "shoot and destroy" meteors travelling through space. This condition used a wider range of disparities between the virtual distances of objects, as meteors approached from optical infinity (more than 6 metres) to peri-corporeal space (40 cm). The fourth group was presented with the same disparities of virtual distance as the third group, but participants were required to fixate constantly on a cross that oscillated from virtual infinity to 40 cm in a sinusoidal fashion at a frequency of 0.3 Hz. A control condition for the fourth group was also included, by having participants track a real object in space over the same disparity range.

Results showed that for the first three groups there were no changes on any measure of binocular function, and none of the participants in these groups showed a clinically significant change in visual status. In the fourth group, there were significant changes in distance vision/visual acuity, visual discomfort, distance heterophoria, distance-associated heterophoria, and near-associated heterophoria. Near heterophoria was the only measure unaffected. In six of the seven participants the changes were clinically significant. The remaining participant reported having trouble in fusing the cross, and managed to do so only 25% of the time. No changes were observed in the control condition for this fourth group. This study demonstrated that stereoscopic information in a display does not necessarily cause visual symptoms or physiological changes, but that a task presenting a continual conflict between accommodation and vergence, and thus stimulating the visual system to adapt continually, does lead to noticeable changes in measures of binocular function. Only the problematic fourth group reported subjective visual symptoms, implying that subjectively reported symptoms could be a good indicator for the rapid evaluation of a display.

4. Other Phenomena Associated with Cybersickness

Two subjectively experienced phenomena that have been linked with cybersickness are vection and sense of presence. In the case of vection, common observations have now been supported by experimental evidence that the phenomenon can influence the occurrence of cybersickness. The relationship between the sense of presence and cybersickness is less clear and the small amount of experimental evidence is contradictory. However, if these phenomena can influence either the incidence or the severity of symptoms experienced, then factors that enhance vection or sense of presence are worthy of consideration.

4.1 Vection

Vection is an illusion of self-motion that is induced by viewing optical flow patterns. It can be induced by viewing visual representations of motion in any of the linear or rotational axes of the body. The occurrence of illusions of self-motion is not restricted to viewing visual displays. For example, such illusions can occur in situations where the sudden backward motion of an adjacent car or train carriage induces a perception of apparent forward self-motion. There is a neurological basis to the experience of vection, as evoked responses have been recorded in the vestibular nuclei of rabbits, cats, and monkeys in response to vection-inducing displays [Hettinger, Berbaum, et al. 1990]. The distinction needs to be made between vection, the experience of illusory self-motion, and the perception of a motion display that depicts self-motion but does not induce a concomitant experience of movement. The former may involve vestibular events, while the latter probably does not [Kennedy, Hettinger, et al. 1990]. The former may also therefore be implicated in causing sickness.

It has been a common observation that vection usually precedes the onset of symptoms of simulator sickness or VIMS [see review in Hettinger & Riccio 1992]. However, there has been little research into the relationship between the two. One exception is the study of vection in a fixed-base flight simulator by Hettinger, Berbaum, et al. [1990]. In this study stationary subjects passively viewed three 15-minute computer-generated flight scenarios that had previously been demonstrated to induce simulator sickness in susceptible subjects. Each of these scenarios showed repeated banks, turns, and apparent altitude changes. While viewing, the subjects continuously recorded the strength of their experienced vection, if any. However, because participants reported either a great deal of perceived vection or none at all, the measure was treated as dichotomous. Motion sickness symptoms were recorded before viewing the first scenario, between each scenario, and after viewing the last scenario. A significant association was found between the experience of vection and motion sickness symptoms, with only one of the five subjects who reported no vection becoming sick, but eight of the ten subjects who experienced vection subsequently becoming sick. This result did support the previously untested observation that visual displays producing vection in observers are more likely to induce cybersickness.

Kennedy, Hettinger, et al. [1990] have recommended the study and identification of properties of displays that promote vection, with the expectation that modification of vection-producing properties would reduce sickness. They also recommended evaluation of the training utility of simulator displays that did not produce illusory self-motion. It had earlier been believed that greater realism of a display, which could include vection-producing properties, would enhance training. However, subsequent work with simulators has shown that greater realism does not necessarily enhance training and often causes more severe simulator sickness. Whether vection itself contributes to the training effectiveness of simulator displays, or to the effectiveness of VEs in general, remains largely untested. The problem is further complicated by findings that not all instances of vection, even vection that can produce postural sway, lead to sickness. Rather, it is possible that the frequency and amplitude characteristics of perceived roll, pitch, yaw, and velocity changes, are important [Kennedy, Hettinger, et al. 1990].

Some factors have been identified as inducing both greater vection and more severe motion sickness symptoms. For example, many wide field-of-view displays have been shown to cause both a strong experience of vection and a greater incidence of symptoms [Pausch et al. 1992]. Hu et al. [1997], in studying VIMS, found that the spatial frequency of a vertically striped rotating drum determined both the amount of reported vection and the degree of sickness in subjects observing the drum from the inside. Spatial frequencies either less or more than the most nauseogenic frequency induced less experience of vection. Others have found that the amount of vection may not always determine the degree of sickness. Prothero, Draper, Furness, Parker, and Wells [1999] carried out experiments with HMDs in which a see-through display allowed the viewing of an independent visual background (IVB) consistent with the subjects' inertial rest frame. When head movements were made while viewing a rotating display, the presence of the IVB in the background reduced both post-exposure ataxia and sickness symptoms, but did not reduce the experience of vection. This suggests that vection does not necessarily produce sickness in all circumstances. More research is needed to understand the association between vection and cybersickness.

4.2 Presence

The sense of presence has been defined as the subjective experience of being in one place or environment even when one is physically located in another. In the case of VEs, a sense of presence describes the participants' experience of being in the computer-generated environment rather than in their actual physical location. Generating a strong sense of presence has in many cases been seen as a design ideal, as it has been assumed that presence would enhance performance in VEs. However, there is at present little evidence to support this [Draper, Kaber, & Usher 1998; Stanney & Salvendy 1998]. Much of the research to date on presence, sometimes termed telepresence, has focussed on its definition and methods of measurement. Most measures have been subjective and have used rating scales or questionnaires [eg Slater, Steed, McCarthy, & Maringelli 1998; Witmer & Singer 1998]. Other subjective measures have been proposed, including paired comparisons (judging which of two VEs produces the greater presence), and cross-modality matching (for example, adjusting the brightness of a light to match the strength of sense of presence) [Stanney & Salvendy 1998]. One study [Nichols, Haldane, & Wilson 2000] also used the more objective measure of observing reflexive responses to startle stimuli in the VE.

Several factors have been observed to enhance the sense of presence. These include ease of interaction with the VE, the degree of user-initiated control, pictorial realism, length of exposure to the VE, and social and system factors [Stanney & Salvendy 1998]. Meaningfulness in the VE can also enhance presence, as shown by a study using chess and non-chess players. Chess players at all levels of ability found that a display of meaningful chess positions enhanced their sense of presence, while meaningless chess positions did not. Non-chess players showed no effects [Hoffman, Prothero, Wells, & Groen 1998]. An important factor that may contribute to presence is vection [McCauley & Sharkey 1992]. Because vection can also be associated with cybersickness, this suggests the possibility of a complex relationship between vection, presence and cybersickness.

The few studies to have directly tested the relationship between presence and cybersickness have found conflicting results. Welch [1997] hypothesised a negative relationship between the two, in which highly veridical VEs produced both a strong sense of presence and no sickness because there was nothing to which the participants needed to adapt. More imperfect VEs would then be expected to produce both less presence and more sickness during adaptation. This association has found some support. Witmer and Singer [1998] used their Presence Questionnaire (PQ), an internally consistent questionnaire with high reliability, to measure presence, and the SSQ to measure cybersickness symptoms. Across four experiments, they consistently found a negative correlation between PQ and SSQ scores, so that less presence was consistently associated with more cybersickness. However, others have found a different result. Wilson, Nichols, and Haldane [1997] found a positive relationship between cybersickness symptoms as assessed by the Short Symptom Checklist, and presence as assessed by a subjective questionnaire, a secondary task, and by observational measures. It should be noted here that different measures were used, and this may have contributed to the conflicting results. In a later study, Nichols et al. [2000] did find a negative correlation between the scores on the interface subscale of the PQ and scores on the SSQ. They concluded that sickness symptoms might have reduced feelings of presence in the VE. Finally, it has been suggested that the process of adaptation to a VE may result in an enhanced sense of presence {Welch 1997], but this remains to be tested. Overall, the exact nature of the relationship between presence and cybersickness has not been established, and further research is needed.

5. Prevention, Management and Treatment of Cybersickness

As shown in the preceding sections, cybersickness is a complex problem. Wilson [1997, p. 1073] noted that the "sheer range and diversity of the potential influencing factors, as well as the rapidly changing nature of VR technology, prevents a full systematic examination of all combinations of all levels of factors". This means that the problem of attempting to prevent or manage cybersickness is also complex. The situation is further complicated by the polysymptomatic nature of cybersickness, where different factors have been implicated in different cybersickness dimensions. For example, some factors relating to the visual display can induce oculomotor symptoms in the absence of motion-sickness-like symptoms. In contrast, other factors may induce motion sickness but no visual symptoms. Thus a variety of measures may be needed, depending on the

VR/VE system being used, the task being performed, and the characteristics of the individual user. Thus a rational approach would attempt to prevent or at least minimise symptoms by addressing known influencing factors where possible, and then consider management of symptomatology that cannot be avoided or prevented.

5.1 Prevention of Cybersickness Symptoms

While improvements brought about by rapidly developing VR technology should with time reduce some of the symptoms caused by factors such as lags in the display or poor position tracking, for a given VR system it may not be possible to prevent or avoid symptoms for all combinations of VE, associated task, and individual participant. However, careful attention to how the system is calibrated and how it is used can reduce cybersickness incidence or severity. A number of authors have mentioned the importance of correct calibration or adjustment of a system in the avoidance of visual symptoms. This could either be the correct alignment and focus of projection channels for a simulator or screen display [Kennedy, Hettinger, et al. 1990], or the appropriate adjustment and calibration of an HMD [Howarth 1999; Wann & Mon-Williams 1997].

In designing the VE, factors that have been shown to induce symptoms can be modified. For example, the rate of global visual flow is a powerful factor in inducing both vection and symptoms and should be restrained, particularly for longer duration displays or with novice participants [McCauley & Sharkey 1992]. This also means that flythroughs should be either at high altitude or low speed, with rapid changes in altitude avoided. Because a wide field-of-view display can increase the incidence of both vection and cybersickness, reducing the field-of-view for otherwise nauseogenic displays, such as fly-throughs showing aggressive manoeuvres, may avoid symptoms [Kennedy, Hettinger, et al. 1990]. Ensuring that participants view the display from within the viewing region, where they have a clear and undistorted view of the scene, can also reduce the incidence of symptoms {Pausch et al. 1992]. A greater degree of control over either movement within the VE or of the visual display can be protective of symptoms [Chance et al. 1998; Pausch et al. 1992], and so would be recommended for VEs with greater apparent self-movement. The method of navigation through the VE also needs consideration, although care must be taken in selecting the method. For example, Regan and Ramsey [1996] found, contrary to expectations, that using an exercise bike to navigate through a VE caused more symptoms than navigating with a conventional 3D mouse.

Attention also needs to be given to the design of the task to be performed in the VE. Duration of exposure to the VE has been rated as one of the most important factors in the occurrence of symptoms [Kennedy et al. 2000]. While adaptation, which is discussed below, increases the length of exposure that can be tolerated without symptoms, it is generally recommended that novice participants limit the duration of their initial exposure to a VE. Because postural instability is believed by some to precede the onset of further symptomatology, it has been recommended that viewers be securely seated for vection-inducing displays [Stoffregen & Smart 1998]. Head movements in the presence of perceived self-movement are particularly nauseogenic, so that tasks should be designed to avoid excessive head movements in displays that induce perceived self-motion [Kennedy, Hettinger, et al. 1990]. Head rests could also be used to support the head.

Some individuals are particularly susceptible to sickness in a variety of provocative situations. These individuals may often be identified by a past history of motion sickness [Golding 1998]. Thus screening potential participants may offer some protection to those who are most susceptible. Although some individuals are more susceptible than others, state variables such as fatigue, illness, hangover, recent vaccination or even recent illness can render any individual more susceptible than they might be normally. Consequently it would be recommended that participants be screened before exposure to ensure that they are in their usual state of health. A history of visual difficulties may also be a caution against a possibly greater risk of oculomotor symptoms.

In general, management practices for participants in VEs could parallel the exposure management practices in flight simulators. These give a number of recommendations designed to minimise both simulator sickness and unsuspected after effects. They include recommendations for limiting exposure until well adapted, minimising rates of visual flow by avoiding unnecessary aggressive or unusual manoeuvres, minimising head movements, and screening individuals before exposure. Importantly, there are recommendations for adaptation schedules, and for allowing recovery time before engaging in potentially dangerous activities such as driving or undertaking scheduled flights [Kennedy, Hettinger, et al. 1990; McCauley & Sharkey 1992]. The risk of after effects needs special consideration, as individuals may be unaware that symptoms may continue beyond the exposure time in the VE. Following immersion in a VE, participants should not be allowed to leave until fully recovered, and their postural stability checked [Kennedy & Stanney 1996].

5.2 Management and Treatment of Cybersickness

The most potent measure for reducing the symptoms of nausea and postural instability is adaptation. This is best achieved by distributed exposures of short duration. Studies of adaptation in flight simulators indicated that there was an optimum time between exposures. For example, Kennedy, Lane, et al. [1993] found that symptoms were least when two to five days were allowed between simulator hops. Studies of VIMS using an optokinetic rotating drum showed that limiting exposure duration to avoid symptoms also facilitated adaptation. Hu and Hui [1997] studied two groups of subjects who viewed the rotating drum every two days. The group that were allowed to stop viewing as soon as they experienced any nausea showed faster adaptation than the group that continued to view the drum for the full session, despite symptoms. Hu and Hui concluded that classical conditioning might impede adaptation. Because individuals differ in susceptibility, adaptation programs need to be tailored to suit the individual. For example, for individuals whose history indicated that they could be more susceptible, early exposures should be kept short. These individuals would be expected to need more exposures to reach adaptation.

Adaptation to the VE needs to take account of more than just the period of immersion, as while symptoms during exposure decrease with adaptation, after effects can become more problematic. After effects have usually been dealt with by having participants avoid for a time any activities that could be impaired by symptoms of instability, or by perceptual after effects. Recently, Stanney and Salvendy [1998] have suggested that real world tasks be practiced to re-adapt during the period following exposure. The tasks that would most benefit from such practice are those that have been performed in the VE, and those that participants will need to perform during the post-immersion period. This procedure could effectively produce a form of dual adaptation to both virtual and real environments, thus minimising symptoms both during and after exposure.

Adaptation may also be useful in minimising visual symptoms, although this remains to be tested for VEs. It has been established that adaptation occurs to the use of prism spectacles, and that this adaptation is retained for some time. With considerable training, subjects learned to adapt to two conflicting prism displacements, consistent with a “learning to learn” paradigm [McGonigle & Flook 1978]. Welch, Bridgeman, Anand, and Browman [1993] found that alternating prism exposure caused dual adaptation as well as resulting in generalisation to novel displacements. Adaptation to visual displacement has also been reported from studies using see-through HMDs [Biocca & Rolland 1998], where initially reduced hand-eye coordination and speed improved with practice, and negative after effects were observed. Whether humans can adapt to changes in the accommodation-vergence links remains to be tested. However, the dual adaptation studies do suggest that with suitable training individuals may learn a dual adaptation to the real and virtual environments, which in turn may avoid problematic after effects.

A major disadvantage with the use of adaptation to eliminate cybersickness, or indeed any motion-sickness-like symptoms, is that adaptation is usually specific, with relatively little transfer of protection from one environment or situation to another. Also, highly susceptible individuals tend to adapt very slowly, and sometimes not at all. This has led to the investigation of a number of specific measures to manage symptoms. One approach is based on the hypothesis that individuals rely on a selected rest frame, the reference frame judged to be stationary and used as a comparator for spatial judgements. If observers can perceive a rest frame that is matched to their physical inertial environment, then sensory conflict should be reduced and symptoms thereby decreased or eliminated. Prothero et al. [1999] investigated the effectiveness of an independent visual background (IVB) in providing a cue for the selected rest frame. They studied subjects who used an HMD to view a display depicting circular motion in yaw. The HMD was used once in see-through mode, where the visible laboratory surroundings provided the IVB, and once in occluded mode, which showed no IVB. In their first experiment, where subjects were required to make head movements while viewing, Prothero et al. found both subjectively reported symptoms and objectively measure ataxia to be reduced by the IVB. They also found an interaction effect in that subjects showed much greater ataxia if they viewed the occluded display first, possibly as learning to control posture was much more difficult with no IVB. A second experiment added a visual task that required subjects to report observations from the moving display, but required no head movements. Overall, ataxia was lower in the second experiment, possibly due to the absence of head movements, but was still reduced by the IVB. Again in the second experiment, viewing the occluded display first resulted in much greater ataxia.

Duh, Parker, and Furness [2001] extended the investigations of IVBs using a grid superimposed on a moving display that was projected on a three foot dome to provide a 180 × 180 degree field-of-view. The display could be rotated (rolled) either at a low frequency of 0.05 Hz or a high frequency of 0.8 Hz. Low frequencies of approximately 0.05 Hz had previously been shown to cause both nausea and instability, while higher frequency rotations had not. The grid providing the IVB could be displayed at two brightness levels: dim and bright. Their results showed that visibility of the IVB, whether dim or bright, reduced postural instability for the low frequency scene oscillation. No effect of the IVB was found for the higher frequency scene motion, which did not of itself perturb postural stability. Overall, the results of the studies of IVBs show promise for reducing nausea and postural instability in VEs. The researchers in this field do, however, note that the use of an IVB may reduce both vection and presence. It is also possible that the IVB may prove distracting with some displays, a factor that still needs investigation.

An alternative approach has considered the use of prior training to reduce individual susceptibility. Parker and Harm [1992] have suggested that the ability to perform mental rotations may be protective against motion sickness symptoms in VEs, and that mental rotation ability could be used both to screen for susceptible individuals and as training prior to use of VEs. Mental rotation allows the recognition of familiar shapes when they are presented in unusual orientations, as would happen in the microgravity of space flight or when viewing through lenses that invert the visual scene. Anecdotal reports from astronauts have described experiences early in their spaceflight of looking at the Earth and perceiving it as “down”, and then looking back to the interior of the spacecraft and perceiving the cabin as “upside-down”. These experiences were both disturbing and provocative of motion sickness symptoms. After a few days in orbit the astronauts were readily able to shift between Earth-referenced down and cabin-referenced down, suggesting the development of mental rotation abilities. Also, cosmonauts who had trained in mental rotation prior to spaceflight found that their mental rotation performance improved further during the space mission, suggesting that their training was further enhanced by active practice during the flight. Based on these reports, Parker and Harm have recommended training in mental rotation ability to reduce susceptibility to symptoms, but as yet no study of the effects of such training has been reported. Stanney et al. [1998] agreed that mental rotation tests could be useful for screening purposes. However, based on Witkin’s [1950] studies of spatial orientation ability and the high reliability of tests that measure mental rotation ability, they claimed mental rotation ability to be innate and therefore not readily learned. The usefulness of training in mental rotation has yet to be tested.

Another method aimed at reducing individual susceptibility has been investigated as a potential means of avoiding space motion sickness. Cowings [1990] reported a series of studies in which tolerance to stimuli that provoke motion sickness was increased by use of biofeedback and autogenic training prior to exposure. This method could also be applicable for reducing cybersickness susceptibility. Autogenic training is a stress reduction technique in which cognitive imagery is used to bring about a state of relaxation, with concomitant physiological changes such as reduced heart and respiratory rates and decreased muscle tension. The method consists of a series of self-suggestions of bodily sensations, such as warmth and heaviness in the limbs [Benson 1993]. Cowings combined autogenic training with biofeedback, in which both visual and verbal feedback were given on the state of the subjects' physiological responses, enabling control over those responses to be learned. She claimed that the two techniques combined were more effective than either used alone. In a series of formal investigations conducted over a 12-year period, using a rotating chair as stimulus and test for motion sickness, the combined training was shown to increase tolerance, with experimental subjects tolerating many more rotations without symptoms. The training could be used as either a preventive method or a countermeasure for motion sickness that started to develop. There was some evidence of transfer to different directions of rotation, and both moderately and highly susceptible individuals showed a similar increase in tolerance. Distributed training schedules, with tests separated by five days, were found to be more effective than massed schedules in which tests were separated by only one day. Finally, male and female subjects responded equally well to the training.

Cowings' method of autogenic feedback training was tested for its effectiveness in the prevention or reduction of space sickness. Four Spacelab-3 astronauts took part in the experiment, with two astronauts undergoing the autogenic feedback training as part of their preflight training schedule, while the other two acted as controls. After training both treatment subjects showed increased tolerance to motion sickness when tested in the rotating chair, and during the subsequent space mission both experienced less sickness than the controls. One had no severe symptom episodes during the flight and the other had only one severe symptom episode. In contrast, both control subjects, who took anti-motion sickness medication, suffered multiple symptom episodes early in the mission. These preliminary results are promising, particularly as the training showed benefits in preventing sickness both in the rotating chair and also during space flight. This suggests that the method could also be worth investigating for prevention of cybersickness.

Biofeedback has also been tested alone as a preventive measure for motion sickness, and has been compared with behavioural and combined behavioural/biofeedback treatments. Dobie, May, Fischer, Elder, and Kubitz [1987] used a behavioural treatment consisting of confidence building and adaptation, which for their studies they termed desensitisation, and EMG and skin temperature biofeedback. The effectiveness of the biofeedback and behavioural treatments, tested individually and in combination, was assessed for resistance to visually induced motion sickness (VIMS). Biofeedback training alone was found to be ineffective, but the behavioural treatment used either alone or in combination with biofeedback did increase tolerance to VIMS. The same research group tested the effectiveness of desensitisation (adaptation) and of cognitive-behavioural therapy, again both alone and in combination. They found that the cognitive-behavioural therapy, either alone or combined with the desensitisation, increased tolerance to VIMS. However, the desensitisation alone was found to be ineffective [Dobie, May, Fischer, & Bologna 1989]. This last finding is contrary to those from most studies of motion, simulator and cybersickness, in which adaptation has been found to be one of the most powerful treatments. The disparity between the biofeedback results of Cowings [1990] and Dobie et al. [1987] is also of some concern, although it could be attributed to differences in experimental methodology and procedure. The participants in the study of Dobie et al. did not achieve control of skin temperature, and although they achieved some electromyogram control they were not able to use this during motion stimulation. Cowings did not report her participants' degree of control of autonomic responses.

The effect of biofeedback, and of autogenic training, on motion sickness was further explored by Jozsvai and Pigeau [1996], who took into account the theoretical aspects of both biofeedback and motion sickness. They questioned whether any of the treatment effects reported by Cowings were attributable to the biofeedback training, or whether a placebo effect had enhanced the effects of autogenic training. They therefore planned to evaluate whether increased control over autonomic nervous system responses was gained through the specific effect of biofeedback, and whether such learned control affected tolerance to motion sickness. This could be evaluated by combining autogenic training with either true or false feedback; as if biofeedback facilitated the learning of autonomic self-regulation, then autogenic training with true feedback about the autonomic responses should be more effective than autogenic training with false feedback. These two conditions could also be compared with a control group to test whether autogenic training, with either true or false feedback, increased tolerance to motion sickness.

For six weeks, Jozsvai and Pigeau exposed a control group and two treatment groups of subjects to weekly sessions of rotation in a Coriolis chair. Between the first and second sessions the two treatment groups were given autogenic training with accompanying true or false feedback on skin temperature and heart rate. Results showed that both treatment groups, regardless of type of feedback, learned to increase their skin temperature and decrease their heart rate, suggesting that control over these responses resulted from the autogenic training and was not due to biofeedback. However, testing during subsequent sessions showed that learned control of skin temperature and heart rate was not related either to tolerance of the Coriolis stimulation or to severity of motion sickness symptoms. Further, the autogenic-feedback training was not effective in preventing the changes in both skin temperature and heart rate that occur during motion sickness. In assessing the usefulness of the treatments as a preventive measure for motion sickness, only the group that received the true feedback showed increased tolerance for rotations and lower scores of motion sickness symptoms. While these results do show that the effectiveness of the combined autogenic-feedback training was not due to learned control of autonomic responses, and are therefore of theoretical interest, they do confirm the practical effectiveness of the combined training for increasing tolerance to motion sickness stimuli. These results, taken together with those of Cowings [1990], indicate that the combined training may provide a potential countermeasure against cybersickness.

Finally, pharmacological countermeasures may be effective against symptoms of the nausea dimension of cybersickness. A number of drugs, including antihistamine and anticholinergic medications, have been found to reduce susceptibility to true motion sickness when taken an hour or two prior to travel. These drugs may also increase the rate of habituation or adaptation [Murray 1997; Wood 1990]. Regan and Ramsey [1996] investigated the efficacy of the anti-motion sickness drug hyoscine hydrobromide in reducing side effects of VEs. One group was administered the drug 40 minutes prior a 20-minute immersion in a VE presented via an HMD, while the control group was given a placebo. The experimental group showed a substantially reduced incidence of self-reported malaise, as well as less severe symptoms when they did occur, indicating that the drug was useful in preventing or reducing the nausea and associated symptoms of cybersickness. One disadvantage of anti-motion sickness medications is that they may cause side effects of drowsiness and impairment of short-term memory [Stott 1990]. However, Regan and Ramsey noted that for the dosage of hyoscine given in their study there was little if any evidence in the literature of associated performance decrements. They therefore concluded that for all but very susceptible individuals, hyoscine medication might prove a useful means of reducing cybersickness susceptibility.

6. Cybersickness and Performance

Cybersickness is of concern for more than health and safety reasons. It is also of concern for its potential effects on performance, as these may reduce or negate many of the advantages to be gained from the use of VEs. It is commonly assumed that cybersickness would have a detrimental effect on performance; just as it is commonly assumed that motion sickness impairs performance. However, research so far on the effects of cybersickness on performance in VEs has been very sparse. Consequently, most existing evidence comes from research on motion sickness and performance, and importantly from studies of simulator sickness and performance. For VEs, a distinction needs to be made between the effects of the motion-sickness-like symptoms of nausea and ataxia, and the effects of the perceptual distortions occurring with 3D displays, although the latter can be related to visual symptoms. Effects would also be expected to differ, often quite markedly, between adapted and unadapted individuals.

In a review of the research on motion sickness and performance, Hettinger, Kennedy, and McCauley [1990] noted considerable confusion as to whether performance was disrupted, and whether any disruption that did occur was attributable to the motion, to the motion sickness, or to other factors. They suggested that observed decrements in performance that did occur with motion sickness were due to distraction, lowered motivation, and an inability to cope, observing that some individuals showed little or no degradation of performance, while others were unable to perform at all. However, they noted that for research in the area to proceed, a large number of procedural issues needed to be addressed. Studies were often not comparable due to the lack of a performance test battery and lack of consistency in reporting conventions. Many studies lacked statistical power, there were logical inconsistencies in interpretation, and large individual differences obscured some results. These issues are equally relevant in assessing the effects of VEs and cybersickness. Nonetheless, some consistent effects of motion and motion sickness have been reported. In a more recent review, Wertheim [1998] differentiated between the general effects and specific effects of motion, and motion sickness, on performance. General effects occurred when motion, whether real or simulated, reduced motivation (due to motion sickness), increased fatigue (due to increased energy requirements), or created balance problems. The only specific effects consistently reported occurred as a result of biomechanical influences on particular skills, for example when interference with oculomotor control disrupted perception, or when movement affected motor skills in a manual tracking task. There was no evidence for direct effects on performance in cognitive tasks, including tests of attention, memory, and pattern recognition.

Of particular relevance to VEs are findings on the effects of simulator sickness. Navy and Marine Corps aviators underwent a battery of tests before and after their regular simulator training. Tests included grammatical reasoning, spatial ability, and finger tapping, as well as both standing and walking steadiness. Results from several simulators showed significant decrements in postural equilibrium following simulator exposure, but cognitive and psychomotor performance scores were largely unaffected. The researchers did note, however, that the usual training function appeared to be suppressed [Hettinger, Kennedy, et al. 1990].

Some studies have been done investigating the effects of VE exposure on task performance. In a preliminary evaluation of assessment methods for the effects of VEs, Nichols, Cobb, & Wilson [1997] administered a number of tests to subjects before and after they carried out a series of tasks in an HMD-generated VE. Tests used included measures of postural stability, motor control, and perceptual judgement. At the same time task difficulty ratings were recorded, and the SSQ was used to assess cybersickness symptomatology. Although the SSQ showed an increase of symptom scores on all subscales from pre- to post-immersion, no significant effects were found on tests of fine motor control, spiral tracing, and dynamic postural stability. However, subjects did significantly underestimate the distance they could reach following exposure to the VE. Subjects also reported experiencing increased levels of difficulty in carrying out the tests following VE exposure. The researchers did not evaluate the possible relationship between task difficulty and SSQ scores. It is possible that some of the measures used lacked sensitivity, particularly as postural instability showed no significant increase, and increased postural instability has been one of the reliable findings following VE exposure in other studies.

The previous study was followed up with an experimental program of research to assess potential effects of participating in VEs delivered via HMDs [Cobb et al. 1999]. The series of nine experiments employed a variety of VR systems, VE designs, and task requirements. In all experiments, participants reported an increase in cybersickness symptoms following immersion. An increase in objectively measured body sway was also reported. But no changes were found in the performance tests of fine and gross motor movement or spiral tracing, or in the cognitive test of Paced Auditory Serial Addition, although subjective difficulty of the latter task increased following immersion. Again, the authors did not report any assessment of the association between subjective difficulty and cybersickness symptomatology. Visual perception of reach distance was again affected by immersion, and subjective difficulty of this task also increased. These results are consistent with the effects of motion and motion sickness, in which symptoms of nausea and postural instability are increased, and motor tasks show decrements only when disrupted by the movement, while cognitive tasks show no effects. The effect on visual perception is consistent with the effects of wearing distorting prism spectacles, which affect both perception of reach distance and pointing accuracy [McGonigle & Flook 1978; Welch et al. 1993]. This last comparison raises the issue of adaptation, and the possibility of dual adaptation which may not only decrease symptoms of cybersickness but may also be relevant for performance of perceptual tasks carried out during and after immersion in the VE.

Stanney and Salvendy [1998] noted that it was common for performance to be poor when participants first entered an unfamiliar VE. During their first immersion in a VE participants often made movements that were jerky and uncoordinated, but as they adapted to the mismatches between the cues provided by the visual scene and those provided by actual body position and movement, their movements became smoother and better coordinated. Because the same perceptual mismatches can cause cybersickness and after effects, as well as disrupt perception both during and after VE immersion, adaptation to the mismatches should provide a solution to both problems. The ideal solution would produce a dual adaptation to both VE and real world.

7. Summary and Conclusions

Cybersickness, the result of unintended side effects of participation in VEs, is a complex problem that can reduce the effectiveness of VEs and cause potential health and safety problems. It has symptoms in common with motion sickness, and both symptoms and dimensions in common with simulator sickness (which may be considered as an example of cybersickness) and other visually induced motion sickness (VIMS). The diverse symptoms can be grouped into three dimensions: nausea or stomach discomfort, disorientation or postural instability, and oculomotor effects (eyestrain or blurred vision). The most commonly accepted causes of cybersickness are the sensory and perceptual mismatches that occur between the visual and vestibular systems. Although rival theories of causation exist, none explains all the complex data on motion, simulator and cybersickness. Cybersickness has been described not just as polysymptomatic, but also as polygenic [Kennedy, Lane, et al. 1993], due to the diversity of both causative factors and symptoms. Factors influencing cybersickness may be associated with the individual participant, the VR/VE system used, or the task being performed in the VE. While advances in VR technology will resolve some of the system problems, other factors influencing cybersickness are more difficult to deal with, and due to individual differences in susceptibility some VE participants will continue to experience symptoms in only mildly provocative VEs. This makes cybersickness difficult to avoid and treat in all situations. Yet a thorough understanding of the problem allows for general awareness of potential adverse effects, as well as possible measures that can be taken to avoid or minimise them. Some specific measures have been recommended, but little research has been carried out and much is still needed. Stanney and Salvendy [1998] have recommended further research to gain an understanding of human adaptation to VEs, along with co-development between VE software and VR hardware to avoid growing sensory discordance problems that would lead to a greater need for adaptation and higher levels of cybersickness. Further research is needed in all areas, both basic and applied.

8. References

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

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

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

Benson, H. (1993) The relaxation response. In D. Goleman & J. Gurin (Eds.), *Mind/Body Medicine*, (pp. 233 – 257) , Yonkers, N.Y., Consumer Reports Books.

Biocca, F. (1992) Will simulation sickness slow down the diffusion of virtual environment technology?, *Presence: Teleoperators and Virtual Environments*, 1 (3), 334 – 343.

Biocca, F. A., & Rolland, J. P. (1998) Virtual eyes can rearrange your body: Adaptation to visual displacement in see-through, head-mounted displays, *Presence: Teleoperators and Virtual Environments*, 7 (3), 262 – 277.

Bles, W., Bos, J. E., de Graaf, B., Groen, E., & Wertheim, A. H. (1998) Motion sickness: only one provocative conflict? *Brain Research Bulletin*, 47 (5), 481 – 487.

Chance, S. S., Gaunet, F., Beall, A. C., & Loomis, J. M. (1998) Locomotion mode affects the updating of objects encountered during travel: The contribution of vestibular and proprioceptive inputs to path integration, *Presence: Teleoperators and Virtual Environments*, 7 (2), 168 – 178.

Cobb, S. V. G. (1999) Measurement of postural stability before and after immersion in a virtual environment, *Applied Ergonomics*, 30 (1), 47 – 57.

Cobb, S. V., & Nichols, S. C. (1998) Static posture tests for the assessment of postural instability after virtual environment use, *Brain Research Bulletin*, 47(5), 459 – 464.

Cobb, S. V. G., Nichols, S., Ramsey, A., & Wilson, J. R. (1999) Virtual reality-induced symptoms and effects, *Presence: Teleoperators and Virtual Environments*, 8 (2), 169 – 186.

Costello, P. J., & Howarth, P. A. (1996) The visual effects of immersion in four virtual environments, *Visual Ergonomics Research Group (VISERG) Report 9604*, Loughborough University.

Cowings, P. S. (1990) Autogenic-feedback training: A treatment for motion and space sickness. In G. H. Crampton, (Ed.) *Motion and space sickness*, (pp. 353 – 372), Boca Raton, Florida, CRC Press.

Crampton, G. H. (Ed.) (1990) *Motion and space sickness*, Boca Raton, Florida, CRC Press.

de Graaf, B., Bles, W., & Bos, J. E. (1998) Roll motion stimuli: sensory conflict, perceptual weighting and motion sickness. *Brain Research Bulletin*, 47 (5), 489 – 495.

Dichgans, J. & Brandt, T. (1973) Optokinetic motion sickness and pseudo-Coriolis effects induced by moving visual stimuli, *Acta Oto-Laryngologica*, 76 (5), 339 – 348.

DiZio, P., & Lackner, J. R. (1992) Spatial orientation, adaptation, and motion sickness in real and virtual environments, *Presence: Teleoperators and Virtual Environments*, 1(3), 319 – 328.

Dobie, T. G., May, J. G., Fischer, W. D., & Bologna, N. B. (1989) An evaluation of cognitive-behavioral therapy for training resistance to visually-induced motion sickness, *Aviation Space & Environmental Medicine,* 60 (4), 307 – 314.

Dobie, T. G., May, J. G., Fischer, W. D., Elder, S. T., & Kubitz, K. A. (1987) A comparison of two methods of training resistance to visually-induced motion sickness, *Aviation Space & Environmental Medicine,* 58 (9, Pt 2), A34 – 41.

Draper, J. V. (1995) Teleoperators for advanced manufacturing: Applications and human factors challenges, *International Journal of Human Factors in Manufacturing*, 5, 53 – 85.

Draper, J. V., Kaber, D. B., & Usher, J. M. (1998) Telepresence, *Human Factors*, 40 (3), 54 – 375.

Duh, H. B-L., Parker, D. E., & Furness, T. A. (2001) An "independent visual background" reduced balance disturbance evoked by visual scene motion: Implication for alleviating simulator sickness, *SIGCHI'01*, 3 (1), 85 – 89.

Durlach, N. I., & Mavor, A. S. (1995) *Virtual reality: Scientific and technological challenges*, Washington, D.C., National Academy Press.

Ebenholtz, S. M. (1992) Motion sickness and oculomotor symptoms in virtual environments, *Presence: Teleoperators and Virtual Environments*, 1 (3), 302 – 305.

Eyeson-Annan, M., Peterken, C., Brown, B., & Atchison, D. (1996) Visual and vestibular components of motion sickness, *Aviation Space & Environmental Medicine,* 67 (10), 955 – 962.

Golding, J. F. (1998) Motion sickness susceptibility questionnaire revised and its relationship to other forms of sickness, *Brain Research Bulletin*, 47 (5), 507 – 516.

Golding, J. F., & Stott, J. R. (1997) Objective and subjective time courses of recovery from motion sickness assessed by repeated motion challenges, *Journal of Vestibular Research*, 7 (6), 421 – 428.

Gonshor, A., & Melville Jones, G. (1976) Extreme vestibulo-ocular adaptation induced by prolonged optical reversal of vision, *Journal of Physiology*, 256, 381 – 414.

Guedry, F. E., Rupert, A. R., & Reschke, M. F. (1998) Motion sickness and development of synergy within the spatial orientation system. A hypothetical unifying concept, *Brain Research Bulletin*, 47 (5), 475 – 480.

Heim, M. (1998) *Virtual realism*, New York, Oxford University Press.

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

Hettinger, L. J., Kennedy, R. S., & McCauley, M. E. (1990) Motion and human performance. In G. H. Crampton, (Ed.) *Motion and space sickness*, (pp. 411 – 441), Boca Raton, Florida, CRC Press.

Hettinger, L. J., & Riccio, G. E. (1992) Visually induced motion sickness in virtual environments, *Presence: Teleoperators and Virtual Environments*, 1 (3), 306 – 310.

Hoffman, H. G., Prothero, J., Wells, M. J., & Groen, J. (1998) Virtual chess: Meaning enhances users' sense of presence in virtual environments, *International Journal of Human-Computer Interaction*, 10 (3), 251 – 263.

Howarth, P. A. (1999) Oculomotor changes within virtual environments, *Applied Ergonomics*, 30 (1), 59 – 67.

Howarth, P. A. & Finch, M. (1999) The nauseogenicity of two methods of navigating within a virtual environment, *Applied Ergonomics*, 30 (1), 39 – 45.

Howarth, P. A. & Hill, K. J. (1999) The maintenance of habituation to virtual simulation sickness. In *Human-computer interaction: Ergonomics and user interfaces, Proceedings of HCI1999*, August 22 – 26, 1999, Vol 1, (pp. 137 – 141).

Hu, S., Davis, M. S., Klose, A. H., Zabinsky, E. M., Meux, S. P., Jacobsen, H. A., Westfall, J. M., & Gruber, M. B. (1997) Effects of spatial frequency of a vertically striped rotating drum on vection-induced motion sickness, *Aviation Space & Environmental Medicine*, 68 (4), 306 – 311.

Hu, S., Glaser, K. M., Hoffman, T. S., Stanton, T. M., & Gruber, M. B. (1996) Motion sickness susceptibility to optokinetic rotation correlates to past history of motion sickness, *Aviation Space & Environmental Medicine*, 67 (4), 320 – 324.

Hu, S., & Hui, L. (1997) Adaptation to optokinetic rotation-induced motion sickness without experiencing nausea, *Perceptual & Motor Skills*, 84(3 Pt 2), 1235 – 1240.

Jozsvai, E. E., & Pigeau, R. A. (1996) The effect of autogenic training and biofeedback on motion sickness tolerance, *Aviation Space & Environmental Medicine*, 67 (10), 963 – 968.

Kawara, T., Ohmi, M., & Yoshizawa, T. (1996) Effects on visual functions during tasks of object handling in virtual environment with a head mounted display, *Ergonomics*, 39(11), 1370 – 1380.

Kennedy, R. S., Berbaum, K. S., & Lilienthal, M. G. (1997) Disorientation and postural ataxia following flight simulation, *Aviation Space & Environmental Medicine*, 68 (1), 13 – 17.

Kennedy, R. S., Dunlap, W. P., & Fowlkes, J. E. (1990) Prediction of motion sickness susceptibility. In G. H. Crampton, (Ed.) *Motion and space sickness*, (pp. 179 – 216), Boca Raton, Florida, CRC Press.

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

Kennedy, R. S., Fowlkes, J. E., & Lilienthal, M. G. (1993) Postural and performance changes in Navy and Marine Corps pilots following flight simulators, *Aviation, Space, and Environmental Medicine*, 64, 912 – 920.

Kennedy, R. S., Hettinger, L. J., & Lilienthal, M. G. (1990) Simulator sickness. In G. H. Crampton, (Ed.) *Motion and space sickness*, (pp. 317 – 341), Boca Raton, Florida, CRC Press.

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

Kennedy, R. S., Lane, N. E., Lilienthal, M. G., Berbaum, K. S., & Hettinger, L. J. (1992) Profile analysis of simulator sickness symptoms: Application to virtual environment systems, *Presence: Teleoperators and Virtual Environments*, 1 (3), 295 – 301.

Kennedy, R. S., Lanham, D. S., Drexler, J. M., Massey, C. J., & Lilienthal, M. G. (1997) A comparison of cybersickness incidences, symptom profiles, measurement techniques, and suggestions for further research, *Presence: Teleoperators and Virtual Environments*, 6 (6), 638 – 644.

Kennedy, R. S., & Stanney, K. M. (1996) Postural instability induced by virtual reality exposure: Development of a certification protocol, *International Journal of Human-Computer Interaction*, 8(1), 25 – 47.

Kennedy, R. S., Stanney, K. M., & Dunlap, W. P. (2000) Duration and exposure to virtual environments: Sickness curves during and across sessions, *Presence: Teleoperators and Virtual Environments*, 1 (3), 463 – 472.

Kolasinski, E. M. (1995) *Simulator sickness in virtual environments*, Technical Report No. 1027. Alexandria, VA.: U.S.A. Army Research Institute for the Behavioral and Social Sciences.

Kolasinski, E. M., & Gilson, R. D. (1999) Ataxia following exposure to a virtual environment, *Aviation Space & Environmental Medicine*. 70(3 Pt 1), 264 – 269.

Lackner, J. R. (1990) Human orientation, adaptation, and movement control. In *Motion sickness, visual displays, and armored vehicle design*, (pp. 28 – 50), Ballistic Research Laboratory, APG, MD, Washington, DC.

Lackner, J. R. (1993) Orientation and movement in unusual force environments, *Psychological Science*, 4 (3), 134 – 142.

Lampton, N. E., Kolasinski, E. M., Knerr, B. W., Bliss, J. P., Bailey, J. H., & Witmer, B. G. (1994) Side effects and after-effects of immersion in virtual environments. In *Proceedings of the Human Factors Society 38th Annual Meeting*, (pp. 1154 – 1157), Santa Monica, CA, Human Factors Society.

Machover, C., & Tice, S. E. (1994) Virtual reality, *IEEE Computer Graphics and Applications*, 14, 15 – 16.

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

McGonigle, B. O., & Flook, J. (1978) Long-term retention of single and multistate prismatic adaptation by humans, *Nature*, 272, 364 – 366.

Miller, E. F., & Graybiel, A. (1970) Motion sickness produced by head movement as a function of rotational velocity, *Aerospace Medicine*, 41, 1180 – 1184.

Mirabile, C. S. Jr. (1990) Motion sickness susceptibility and behavior. In G. H. Crampton, (Ed.) *Motion and space sickness*, (pp. 391 – 410), Boca Raton, Florida, CRC Press.

Mon-Williams, M., Plooy, A., Burgess-Limerick, R., & Wann, J. (1998) Gaze angle: a possible mechanism of visual stress in virtual reality headsets, *Ergonomics*, 41 (3), 280 – 285.

Mon-Williams, M., & Wann, J. (1998) Binocular virtual reality displays: When problems do and don't occur, *Human Factors*, 40 (1), 42 – 49.

Mon-Williams, M., Wann, J. P., & Rushton, S. (1993) Binocular vision in a virtual world: Visual deficits following the wearing of a head-mounted display, *Opthalmic and Physiological Optics*, 13, 387 – 391.

Morrow, G. R. (1985) The effect of a susceptibility to motion sickness on the side effects of cancer chemotherapy, *Cancer*, 55, 2766 – 2770.

Murray, J. B. (1997) Psychophysiological aspects of motion sickness, *Perceptual & Motor Skills*, 85 (3 Pt 2), 1163 – 1167.

Nichols, S. (1999) Physical ergonomics of virtual environment use, *Applied Ergonomics*, 30, 79 – 90.

Nichols, S., Cobb, S. V. G., & Wilson, J. R. (1997) Health and safety implications of virtual environments: Measurement issues, *Presence: Teleoperators and Virtual Environments*, 6 (6), 667 – 675.

Nichols, S., Haldane, C., & Wilson, J. R. (2000) Measurement of presence and its consequences in virtual environments, *International Journal of Human-Computer Studies*, 52, 471 – 491.

Owen, N., Leadbetter, A. G., & Yardley, L. (1998) Relationship between postural control and motion sickness in healthy subjects. *Brain Research Bulletin*, 47 (5), 471 – 474.

Park, A. H. (1998) Age differences in self-reported susceptibility to motion sickness, *Perceptual & Motor Skills*, 87 (3 Pt 2), 1202.

Parker, D. E., & Harm, D. L. (1992) Mental rotation: A key to mitigation of motion sickness in the virtual environment, *Presence: Teleoperators and Virtual Environments*, 1 (3), 329 – 333.

Parker, D. E., & Parker, K. L. (1990) Adaptation to the simulated stimulus rearrangement of weightlessness. In G. H. Crampton, (Ed.) *Motion and space sickness*, (pp. 247 – 262), Boca Raton, Florida, CRC Press.

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

Piantanida, T., Boman, D. K., & Gille, J. (1993) Human perceptual issues and virtual reality, *Virtual Reality Systems*, 1 (1), 43 – 52.

Prothero, J. D., Draper, M. H., Furness, T. A. 3rd., Parker, D. E., & Wells, M. J. (1999) The use of an independent visual background to reduce simulator side-effects, *Aviation Space & Environmental Medicine*, 70 (3 Pt 1), 277 – 283.

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

Regan, E. C., & Price, K. R. (1993a) *Some side-effects of immersion virtual reality*, Army Personnel Research Establishment, Report 93R010.

Regan, E. C., & Price, K. R. (1993b) *Some side-effects of immersion virtual reality: A second immersion,* Army Personnel Research Establishment, Report 93R033.

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

Regan, E. C., & Price, K. R. (1993d) *Some side-effects of immersion virtual reality: The effects of increasing head movements, of rapid interaction, and of seating subjects*, Army Personnel Research Establishment, Report 93R022.

Regan, E. C., & Price, K. R. (1994) The frequency of occurrence and severity of side-effects of immersion virtual reality, *Aviation Space & Environmental Medicine*, 65 (6), 527 – 530.

Regan, E. C., & Ramsey, A. D. (1994) *Some side-effects of immersion virtual reality: An investigation into the effect of two types of movement through a virtual environment on reported nausea*, Defence Research Agency, Report DRA/CHS/TR94009/1.

Regan, E. C., & Ramsey, A. D. (1996) The efficacy of hyoscine hydrobromide in reducing side-effects induced during immersion in virtual reality, *Aviation Space & Environmental Medicine*, 67 (3), 222 – 226.

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

Robinett, W., & Rolland, J. P. (1992) A computational model for the stereoscopic optic of a head-mounted display, *Presence: Teleoperators and Virtual Environments*, 1 (1), 45 – 62.

Rushton, S. K., & Riddell, P. M. (1999) Developing visual systems and exposure to virtual reality and stereo displays: Some concerns and speculations about the demands on accommodation and vergence, *Applied Ergonomics*, 30(1), 69 – 78.

Sharma, K., & Aparna. (1997) Prevalence and correlates of susceptibility to motion sickness, *Acta Geneticae Medicae et Gemellologia*, 46 (2), 105 – 121.

Sheehy, J., & Wilkinson, M. (1989) Depth perception after prolonged usage of night vision goggles, *Aviation Space & Environmental Medicine*, 60, 573 – 579.

Slater, M., Steed, A., McCarthy, J., & Maringelli, F. (1998) The influence of body movement on subjective presence in virtual environments, *Human Factors*, 40 (3), 469 – 477.

Stanney, K. M., & Hash, P. (1998) Locus of user-initiated control in virtual environments: Influences on cybersickness, *Presence: Teleoperators and Virtual Environments*, 7 (5), 447 – 459.

Stanney, K. M., Kennedy, R. S., Drexler, J. M., & Harm, D. L. (1999) Motion sickness and proprioceptive aftereffects following virtual environment exposure, *Applied Ergonomics*, 30 (1), 27 – 38.

Stanney, K. M., Mourant, R. R., & Kennedy, R. S. (1998) Human factors issues in virtual environments: A review of the literature, *Presence: Teleoperators and Virtual Environments*, 7 (4), 327 – 351.

Stanney, K., & Salvendy, G. (1998) Aftereffects and sense of presence in virtual environments: Formulation of a research and development agenda, *International Journal of Human-Computer Interaction*, 10 (2), 135 – 187.

Stern, R. M., Hu, S., LeBlanc, R., & Koch, K. L. (1993) Chinese hyper-susceptibility to vection-induced motion sickness, *Aviation Space & Environmental Medicine*, 64 (9 Pt 1), 827 – 830.

Stoffregen, T. A., Hettinger, L. J., Haas, M. W., Roe, M. M., & Smart, L. J. (2000) Postural instability and motion sickness in a fixed-based flight simulator, *Human Factors*, 42 (3), 458 – 69.

Stoffregen, T. A., & Riccio, G. E. (1991) An ecological critique of the sensory conflict theory of motion sickness, *Ecological Psychology*, 3 (3), 159 – 194.

Stoffregen, T. A., & Smart, L. J. Jr. (1998) Postural instability precedes motion sickness. *Brain Research Bulletin*, 47 (5), 437 – 448.

Stott, J. R. R. (1990) Adaptation to nauseogenic motion stimuli and its application in the treatment of airsickness. In G. H. Crampton, (Ed.) *Motion and space sickness*, (pp. 372 – 390), Boca Raton, Florida, CRC Press.

Turner M., & Griffin M. J. (1999) Motion sickness in public road transport: passenger behavior and susceptibility, *Ergonomics*, 42(3), 444 – 461.

Usoh, M., Catena, E., Arman, S., & Slater, M. (2000) Using presence questionnaires in reality, *Presence: Teleoperators and Virtual Environments*, 9 (5), 497 – 503.

Wann, J. P., & Mon-Williams, M. (1997, May) Health issues with virtual reality displays: What we do know and what we don't, *Computer Graphics*, 53 – 57.

Warwick-Evans, L., A., & Beaumont, S. (1991) An experimental evaluation of sensory conflict versus postural control theories of motion sickness, *Ecological Psychology*, 7, 163 – 179.

Warwick-Evans, L. A., Symons, N., Fitch, T., & Burrows, L. (1998) Evaluating sensory conflict and postural instability. Theories of motion sickness, *Brain Research Bulletin*, 47 (5), 465 – 469.

Welch, R. B. (1997) The presence of aftereffects. In G. Salvendy, M. Smith, & R. Koubek, (Eds.) *Design of computing systems: Cognitive considerations*, (pp. 273 – 276), Amsterdam, Elsevier.

Welch, R. B., Bridgeman, B., Anand, S., & Browman, K. E. (1993) Alternating prism exposure causes dual adaptation and generalization to a novel displacement, *Perception & Psychophysics*, 54 (2), 195 – 204.

Wertheim, A. H. (1998) Working in a moving environment, *Ergonomics*, 41 (12), 1845 – 1858.

Wilson, J. R. (1996) Effects of participating in virtual environments: A review of current knowledge, *Safety Science*, 23 (1), 39 – 51.

Wilson, J. R. (1997) Virtual environments and ergonomics: Needs and opportunities, *Ergonomics*, 40 (10), 1057 – 1077.

Wilson, J. R. (1999) Virtual environments applications and applied ergonomics, *Applied Ergonomics*, 30, 3 – 9.

Wilson, J. R., Nichols, S., & Haldane, C. (1997) Presence and side effects: Complementary or contradictory? In M. Smith, G. Salvendy, & R. Koubek, (Eds.) *Design of computing systems: Social and ergonomic considerations*, (pp. 889 – 892), Amsterdam, Elsevier.

Witkin, H. A. (1950) Individual differences in ease of perception of embedded figures, *Journal of Personality*, 19, 1 – 15.

Witkin, H. A., & Goodenough, D. R. (1977) Field dependence and interpersonal behavior, *Psychological Bulletin*, 84 (4), 661 – 689.

Witmer, B. G., & Singer, M. J. (1998) Measuring presence in virtual environments: A Presence Questionnaire, *Presence: Teleoperators and Virtual Environments*, 7 (3), 225 – 240.

Wood, C. D. (1990) Pharmacological countermeasures against motion sickness. In G. H. Crampton, (Ed.) *Motion and space sickness*, (pp. 343 – 352), Boca Raton, Florida, CRC Press.

Page classification: UNCLASSIFIED

DEFENCE SCIENCE AND TECHNOLOGY ORGANISATION DOCUMENT CONTROL DATA							1. PRIVACY MARKING/CAVEAT (OF DOCUMENT)
2. TITLE Side Effects of Virtual Environments: A Review of the Literature				3. SECURITY CLASSIFICATION (FOR UNCLASSIFIED REPORTS THAT ARE LIMITED RELEASE USE (L) NEXT TO DOCUMENT CLASSIFICATION) Document (U) Title (U) Abstract (U)			
4. AUTHOR(S) Judy Barrett				5. CORPORATE AUTHOR Information Sciences Laboratory PO Box 1500 Edinburgh South Australia 5111 Australia			
6a. DSTO NUMBER DSTO-TR-1419		6b. AR NUMBER AR-012-747		6c. TYPE OF REPORT Technical Report		7. DOCUMENT DATE May 2004	
8. FILE NUMBER N 9505-21-155	9. TASK NUMBER DST 00/090		10. TASK SPONSOR DISL		11. NO. OF PAGES 60		12. NO. OF REFERENCES 116
13. URL on the World Wide Web http://www.dsto.defence.gov.au/corporate/reports/DSTO-TR-1419.pdf					14. RELEASE AUTHORITY Chief, Command and Control Division		

15. SECONDARY RELEASE STATEMENT OF THIS DOCUMENT

Approved for public release

OVERSEAS ENQUIRIES OUTSIDE STATED LIMITATIONS SHOULD BE REFERRED THROUGH DOCUMENT EXCHANGE, PO BOX 1500, EDINBURGH, SA 5111

16. DELIBERATE ANNOUNCEMENT

No Limitations

17. CASUAL ANNOUNCEMENT Yes

18. DEFTEST DESCRIPTORS
Cybersickness
Motion sickness

19. ABSTRACT
Cybersickness symptoms are the unintended psychophysiological side effects of participation in virtual environments. Symptoms can occur both during and after participation, thus having implications for health and safety, user acceptance, and overall system effectiveness. Just as for other visually induced motion sickness, cybersickness is believed to result from sensory and perceptual mismatches between the visual and vestibular systems, and can be considered as a problem of adaptation to altered environments. Symptoms can be grouped into three dimensions: nausea, disorientation or postural instability, and visual symptoms. Numerous factors relating to the individual participants, the virtual reality system and virtual environment used, and the task carried out, can affect either incidence or severity of cybersickness. Taking account of these factors may avoid or minimise symptoms. This report reviews the literature on cybersickness, simulation sickness, and the relevant research on motion sickness, considers measures that have been proposed to manage and treat cybersickness, and identifies areas where more research is needed.

Page classification: UNCLASSIFIED