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CYBERSICKNESS IN THE PRESENCE OF SCENE ROTATIONAL MOVEMENTS IN
DIFFERENT AXES**[Submitted to Applied Ergonomics, referees' comments received,
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Abstract

Compelling scene movements in a virtual reality (VR) system can cause symptoms of motion sickness (i.e., cybersickness). A study has been conducted to investigate the effects of scene oscillations in different axes on the level of cybersickness. Sixteen male were exposed to four 20-minute VR simulation sessions with at least seven-day separation between consecutive exposures. The four sessions used the same virtual environment with scene oscillations in different axes: pitch, yaw, roll and no oscillation (speed: 30°/s, range: +/-60°). Verbal ratings of nausea level were taken at 5-minute intervals and sickness symptoms were measured before and after the exposure using the Simulator Sickness Questionnaire (SSQ). Significant differences were found between the no oscillation condition and the oscillating conditions. With scene oscillation, nausea ratings increased significantly with exposure duration for all the axes of oscillation. Scene oscillations in different axes did not significantly affect the nausea rating and the SSQ scores. The main effects and their interactions are discussed in the paper.

Keywords: Cybersickness, Virtual Reality, Vection, Scene movement

1. Introduction

Head-coupled virtual reality systems were developed to improve the visual interface between human operators and aircraft flight control, navigation, and weapon systems (Birt and Furness, 1974). This technology provides an advanced interface for users to interact with computer-generated (virtual) environments (e.g., Kalawsky, 1993; Earnshaw *et al.*, 1995; Furness and Barfield, 1995; Carr and England, 1995; Vince, 1995). Image projections forming the virtual environment are presented through either a Head-Mounted Display (HMD) or a multiple-screen projection system (e.g., CAVE™). Users can select their views by moving their heads and can navigate through the virtual environment with a mouse or joystick-type device. Virtual reality systems are extensively used for training (e.g., driving simulation: Kuhl *et al.* (1995) and Bayarri *et al.* (1996); flight simulation: Haas (1984); teleoperation: Rod and Pardini (1996); machine operation: Lin *et al.* (1996); and health therapy: Lamson (1997)).

Although virtual reality systems are powerful in generating an apparent sense of presence, they have some shortcomings. One of them is the associated sickness. Users of virtual reality systems may suffer from symptoms similar to those of motion sickness. The term 'cybersickness' has been used to describe the phenomenon of motion sickness with virtual reality systems (McCauley and Sharkey, 1992). Regan (1995) studied the effects of virtual reality simulation. In her study, 61 percent of the 150 subjects reported symptoms of malaise. She stated that after the use of a virtual reality system for 20 minutes, the most common symptoms were dizziness, headaches, eyestrain, stomach discomfort and severe nausea. Five percent of the subjects withdrew from the experiment due to severe nausea or severe dizziness. So (1994) also studied the occurrence of motion sickness with a head-coupled virtual reality system. He reported that about 60 percent (29 out of 48) of the subjects suffered 'general discomfort' after a 20-minute flight simulation. Four subjects had

to withdraw from the study after reporting moderate nausea. A review of literature shows that there are a number of similar studies reporting sickness symptoms among users who navigate through a virtual simulation for 20 minutes or longer (e.g., passive navigation: So and Lo, 1999; active navigation: Finch and Howarth, 1996; Stanney and Kennedy, 1997, 1998; Kolasinski *et al.*, 1998; Draper, 1998). Some studies reported sickness occurrence even after 10 minutes of exposure (e.g., Wilson *et al.*, 1997). Summaries of previous literatures are shown in Table 1. The occurrence of cybersickness has hindered the widespread applications of VR simulators.

[Insert Table 1 about here]

According to the sensory conflict theory (Reason and Brand, 1975; Benson, 1984), cybersickness is a type of visual-induced motion sickness. When an observer views a wide field-of-view moving scene, there is commonly an illusion of self-motion (vection) in the opposite direction of the moving scene (e.g., Griffin, 1990; Oman, 1993). This experience can be nauseogenic. Since cybersickness is a type of visual-induced motion sickness, a logical research direction is to study the effects of visual scene movement on the level of cybersickness. A review of literature indicates that although cybersickness has been the subject of many studies (Table 1), the effects of visual scene movements were rarely studied. Inspection of Table 1 indicates that most studies investigated the effects of parameters affecting *how* visual scene is presented and the effects of subject-related variables. Examples of parameters concerning *how* the scene is presented include: display's field-of-view, types of displays, display lag, and use of stereoscopic presentation (Table 1). Comparatively speaking, the effects of *what* is being presented receive far less

attention. In particular, the axes of scene movement were not controlled in most of the cybersickness studies and there have been no published studies on the effects of scene movement axes on cybersickness. This paper reports a study on rated levels of cybersickness in the presence of rotating scene in different axes. The aim is to identify the dominant axis (axes) of rotational scene movement which is associated with cybersickness occurrences.

In studies of seasickness, Lawther and Griffin (1986) reported that the vertical axis ship motion was the main cause of motion sickness. This conclusion subsequently led to the development of the Motion Sickness Dose Value (MSDV) for predicting seasickness based on the measured vertical motion of a ship (BSI, 1987). Similarly, if a dose value relationship between the rated level of cybersickness and the amount of scene movement in a virtual environment is to be developed, the effects of the scene movement axes should be studied.

2. Method and Design

2.1 Objective and hypotheses

The objective of this study is to determine the relationship between axes of visual scene oscillation and the rated level of cybersickness. It was hypothesized that (i) visual scene oscillations in the pitch and roll axes would produce higher levels of sickness than scene oscillations in the yaw axes; and (ii) a virtual environment without scene oscillations would produce lower levels of sickness. The former hypothesis was based on the assumption that the effects of apparent self-motion in the pitch and roll axes would be larger due to the absence of the appropriate gravitational stimuli.

2.2 Participants

Sixteen male Chinese volunteers participated in the experiment. They were university students and staff members with an average age of 26 years. A payment of HK\$200 was given to each participants at the end of the experiment as a compensation for their time and travel expenses. Participants of the same gender were used in this study because it has been reported that gender has a significant effect on motion sickness susceptibility (Griffin, 1990; So *et al.*, 1999).

2.3 Apparatus

The virtual scene was constructed using a virtual reality authoring software (dVISE) running on a Silicon Graphics Onyx workstation. Images were presented on a VR4 LCD Head-Mounted Display with a field-of-view of 48° horizontal and 36° vertical. Head orientation was monitored with a Polhemus FastTrack system. The experiment room was air-conditioned with an average temperature of about 23°C. The inherent response lag of the experimental virtual reality system to head movement was about 67ms. This comprises 33.3ms computational lag; 16.7ms video frame delay; and 16.7ms head tracker delay.

2.4 Procedure

This experiment investigated three independent variables: (i) duration of exposure (0 to 20 minutes); (ii) axes of scene oscillations (pitch, yaw, and roll axis); and (iii) with and without scene oscillations. It was a within-subject full factorial experiment with four conditions: scene oscillations in pitch, yaw, and roll axes, and no scene oscillation. The order in which the conditions were presented was balanced using four 4x4 Latin square designs and exposure to each condition was separated by at least seven days (10 days, on average). Regan and Price (1993a) reported that repeated exposure to the same virtual environment with separation of less than seven days could affect the levels of

cybersickness. The speed of scene oscillation was 30° per second and the range of oscillation was $\pm 60^\circ$ (i.e., 120°). This speed of oscillation was comparable to speeds used in studies of vection-induced motion sickness caused by rotating drums (e.g., Stern *et al.*, 1989). The range of scene oscillation was an arbitrary choice of what is expected in a typical virtual simulation application. A sample scene is shown in Figure 1. Before each exposure, the subjects were required to rest for five minutes in the air-conditioned experiment room. They were then asked to complete a pre-exposure Simulator Sickness Questionnaire (SSQ) documenting the severity levels of 28 sickness symptoms (Kennedy, *et al.*, 1993). A one-minute practice was given for the subjects to get familiar with the equipment followed by a 20-minute virtual simulation. Nausea ratings were obtained verbally at five-minute intervals according to a seven-point scale: 0 - no symptom; 1 - any unpleasant symptom, however slight; 2 - mild unpleasant symptom; 3 - mild nausea; 4 - mild to moderate nausea; 5 - moderate nausea but can continue; 6 - moderate nausea, want to stop. After the exposure, subjects were asked to complete a post-exposure SSQ and a questionnaire assessing the realism of the simulation. The subjects were then asked to rest for about 10 minutes before they were discharged.

During the 20-minute virtual reality simulation, subjects were asked to sit in an up-right posture with their backs touching the back-rest. Also, they were instructed to keep their heads straight in a forward looking posture. This eliminates the influence of head movement that may be a subject of interest for future studies.

[Insert Figure 1 about here]

3. Results and discussion

The mean nausea ratings obtained with and without scene movements are shown in Figure 2. The figure indicates that ratings increased with increasing exposure time. A normal plot was obtained for the nausea rating measurement and it indicated that the data distribution was normal. An ANOVA (General Linear Model) on nausea ratings was performed and duration of exposure was found to have a significant main effect on nausea ratings ($F_{4,160} = 64.1$, $p < 0.001$, Table 2). Post-hoc analyses using Student-Newman-Keuls (SNK) tests showed that, with scene oscillations (i.e., in pitch, yaw, and roll axes), nausea ratings increased significantly even after five minutes of virtual reality simulation ($p < 0.05$) and nausea ratings obtained at 0, 5, 10, and 15 minutes after the start of the simulation were all significantly different from each other. However, data collected after 15 and 20 minutes of simulation were not significantly different. The effects of exposure duration are illustrated clearly in Figure 3. With scene oscillations in the pitch and roll axes, the rate of increase of nausea rating slowed down after 15 minutes. For the yaw axis oscillation, however, there was no sign of slowing down. Studies with longer duration to further understand this phenomenon is desirable.

[Insert Figures 2 and 3 about here]

[Insert Table 2 about here]

Without scene oscillation (i.e. the control condition), the mean nausea level remained near zero (i.e., 'no symptom') and the effects of duration was not significant for exposure

time up to 15 minutes ($p > 0.1$, SNK test). After 20 minutes of exposure, however, the average nausea ratings were significantly higher than that measured at 0 minute ($p < 0.05$). A possible reason is that, in the condition without scene movement, subjects suffered from some unpleasant symptoms (e.g., fatigue) caused by the Head-Mounted Display (HMD) which weighted 0.94kg. Over half of the subjects complained about the weight of the HMD. This explanation is confirmed by the observation that the highest nausea rating obtained in the condition without scene oscillation was only '1', which corresponds to 'any unpleasant symptom, however slight'. The absence of strong duration effects when there was no scene oscillation suggests that scene oscillation is essential in causing cybersickness. This suggestion is confirmed by the significant main effect of scene oscillation on nausea ratings ($F_{1,160} = 130$, $p < 0.001$, Table 2). This strong effect of scene movement on levels of cybersickness is consistent with the sensory conflict theory which predicts that wide field-of-view scene movement can introduce sense of self-motion illusion (vection), which can then cause symptoms of cybersickness in the absence of appropriate body movement (Reason and Band, 1975; Griffin, 1990; and Oman, 1993). During this experiment, subjects remained stationary while exposed to the various scene oscillations. Table 2 reveals a significant interaction between the effect of duration and the effects of scene oscillation ($F_{4,160} = 9.4$, $p < 0.001$). This interaction effect can be observed in Figure 2, in the presence of scene movement, nausea ratings increase at a faster rate with exposure duration. Based on the experimental findings, a simple conceptual model for cybersickness generation is proposed (Figure 4). This model, predicts, and the experiment verifies, that (i) the presence of scene movement is essential for the occurrence of symptoms of cybersickness; (ii) the levels of cybersickness accumulates with exposure duration; and (iii) there is an interaction between the effects of scene movement and the exposure duration. Although this model seems to agree with the present experimental findings, the parts that predict the generation of 'vection' and 'sensory conflict' will require further confirmation since neither were

measured in the present study. Future studies of cybersickness should include levels of 'self-motion illusion' (vection) as a dependent variable. According to the conceptual model in Figure 4, level of cybersickness could be expressed using the following function:

$$\text{Sickness level} = K_1 \int_0^T (\text{levels of sensory conflict}) dt$$

where T is the exposure duration, and

K_1 is a constant

In the absence of body movement, levels of sensory conflict should be proportional to the levels of 'vection' which, in turn, is proportional to levels of scene movements. Sickness level can, therefore, be expressed as:

$$\text{Sickness level} = K_2 \int_0^T (\text{levels of scene movements}) dt$$

If the levels of scene movement can be measured, the above formulae can be used to predict the level of cybersickness. A similar approach has lead to the successful development of the Motion Sickness Dose Value (MSDV) for predicting the severity level of sea-sickness (BSI, 1987; Griffin, 1990). The MSDV has the following form (Griffin, 1990):

$$\text{MSDV} = \left[\int_0^T (\text{sea movements})^2 dt \right]^{1/2}$$

where T is the duration of a voyage

[Insert Figure 4 about here]

Nausea ratings with scene oscillations in pitch, yaw, and roll axes are shown in Figure 3. It can be observed that after 20 minutes of exposure, the mean nausea ratings with oscillations in three different axes are similar. An ANOVA was performed on nausea ratings obtained in the three conditions with scene oscillations (Table 3). The results indicate that axes of rotational scene oscillation do not have a significant effect on the level of nausea ($F_{2,120} = 1.6$, $p > 0.19$, Table 3). Inspections of Tables 2 and 3 indicate that 'subject' have significant main effects on nausea ratings and the effects of 'subject' have significant interactions with the effects of (i) with / without scene movement; (ii) axes of scene oscillation; and (iii) exposure duration. 'Subject' having a main effect should not be surprising since it has been known that people have different susceptibility to motion sickness (e.g., Lawther and Griffin, 1988; Griffin, 1990). According to a recent survey, the prevalence rates for Hong Kong Chinese adults who rate themselves as not susceptible to motion sickness is $14\% \pm 3\%$; slightly-to-moderately susceptible is $79\% \pm 4\%$; and very-to-extremely susceptible is $7\% \pm 2\%$. Following the same argument, it is logical to expect those with higher susceptibility to cybersickness to be more sensitive to the presence of scene movement and the effects of exposure duration. Plots of the interactions between the effect of subject and axes of scene oscillation did not review any consistent pattern. Further studies with more subjects are needed to investigate the meaning behind this interaction. In the present study, it is reasonable to conclude that, on average, the effect of scene oscillation in pitch, yaw, and roll axes on the level of nausea are not significantly different from each other ($p > 0.19$).

[Insert Figure 4 about here]

[Insert Table 3 about here]

In addition to the nausea ratings, the subjects completed a Simulator Sickness Questionnaire before and after the twenty-minute virtual reality simulation. This questionnaire requires the subjects to rate the severity levels of 28 sickness symptoms (Kennedy *et al.*, 1993). Over 50 percent of the subjects exposed to scene oscillations reported an increase in general discomfort, eyestrain, fullness of head, fatigue, and difficulty in focusing. Total sickness scores and the three associated sub-scores: oculomotor (O), nausea (N), and disorientation (D) are shown as functions of with and without scene movement in Figure 5. The method of computing the SSQ scores was adopted from Kennedy *et al.* (1993 and 1994). Four ANOVA were conducted to analyze the effects of scene movement (with and without) on the four SSQ scores obtained before and after the simulation. The results indicate that the presence of scene movement has a significant effect on all the sub-scores and the total sickness score (nausea sub-score: $F_{1,79} = 9.7$, $p < 0.005$; oculomotor sub-score: $F_{1,79} = 13.9$, $p < 0.0005$; disorientation sub-score: $F_{1,79} = 17.7$, $p < 0.0001$; and total sickness score: $F_{1,79} = 17.3$, $p < 0.0001$). The ANOVA table for the total sickness score is shown in Table 4.

[Insert Table 4 about here]

[Insert Figure 5 about here]

Sickness scores obtained from the three conditions with scene oscillations were extracted and another four ANOVA were performed to investigate the effects of axes of scene oscillation. Results indicate that scene oscillation axes do not have a main effect on all the SSQ scores (nausea sub-score: $F_{1,30} = 2.3$, $p > 0.1$; oculomotor sub-score: $F_{1,30} = 1.2$, $p > 0.3$; disorientation sub-score: $F_{1,30} = 0.9$, $p > 0.4$; total sickness score: $F_{1,30} = 1.7$, $p > 0.19$). The ANOVA for the total sickness score is shown in Table 5.

[Insert Table 5 about here]

With scene movement, the mean post-exposure total sickness score was 35, which is comparable to the published data (19 - 55) documented in Kennedy and Stanney (1997). In this study, the profiles of the post-exposure sickness sub-scores (Nausea (N); Oculomotor (O); and Disorientation (D)) were consistently as $O > D > N$, which was different from the $D > N > O$ pattern reported by Kennedy and Stanney (1997) and the $D > N > O$ and $D > O > N$ patterns reported by Enhrlich and Kolasinski (1998). Since different simulation and display apparatus, virtual environment, and tasks were used in previous studies, it is difficult to account for the differences in sickness sub-score profiles. Kennedy and Stanney (1997) reported that sickness data from non-Virtual Reality simulators have a sickness sub-score profile of $O > N > D$, which is closer to that found in this experiment. Further investigations reviewed that the high level of oculomotor sickness was mainly due to the high level in fatigue and eye-strain symptoms. This may be related to the weight of the helmet (0.94kg) and the short focal length of the projected imagery (about 1 meter in front of the VR4 HMD). It is worth noting that even before the exposure, oculomotor sub-score was consistently the

highest among the three sub-scores for all the conditions. Further investigations on the profiles of pre-exposure and post-exposure sickness scores are desirable.

4. Conclusions and future work

Scene oscillations in pitch, yaw, and roll axes within a virtual environment has been shown to significantly increase the rated level of nausea and simulator sickness (SSQ) scores. Experimental data indicate that, all other things being equal, scene oscillations in different rotating axes will have similar effects on the level of cybersickness. This suggests that there is not a dominant rotational axis around which virtual scene movement will contribute more towards cybersickness.

In the presence of scene oscillations, exposure to a virtual environment for a period longer than five minutes will cause significant increases in nausea ratings. In the absence of scene oscillation, viewing a stationary virtual environment for up to 15 minutes is not likely to cause any significant increase in the nausea level. In this study, all subjects were asked to keep their heads still. Further experiments investigating the interactions between scene oscillations and head movements are desirable.

This study confirms that scene movement in a virtual environment can cause significant increases in cybersickness and its presence will significantly accelerate the increase of nausea ratings with increasing exposure duration. This suggests that if the scene movement in a virtual environment can be measured and quantified, a possible dose value for predicting levels of cybersickness could be formulated by integrating the quantified scene movement with duration. A simple conceptual model for the generation of cybersickness is proposed. With the finding that similar scene movement in different rotational axes will result in similar levels of cybersickness, a single dose formula can be

used for scene movement in different rotational axes. Future work to quantify scene movement in terms of complexity and speed of movement should be very rewarding.

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References

- Bayarri, S., Fernandez, M. and Perz, M. (1996) Virtual Reality for driving simulation. *J. of Commun. ACM (USA)*, Vol.39, No.5, pp.72-6.
- Benson, A.J. (1984) Motion sickness. In: *Vertigo* (Dix, M.R. and Hood, J.S., eds), Chapter 19, pp. 391-426. New York: Wiley.
- Birt, J.A. and Furness, T.A. (1974) Visually-coupled systems. *Air University Review*, 20, pp 28-40.
- Bliss, J.P., Tidwell, P.D., Loftin, R.B., Johnston, B.E., Lyde, C.L. and Weathinton, B. (in preparation) An experimental evaluation of virtual reality for training teamed navigation skills. Technical Report 96-01. Houston, TX: University of Houston Virtual Environment Technology Laboratory.

BSI (1987) Measurement and evaluation of human exposure to whole-body mechanical vibration and repeated shock: BS6841. London: British Standards Institution.

Carr, K. and England, R. (1995) Simulated and Virtual Realities: elements of perception. Taylor & Francis, ISBN 0-7484-0129-6.

Costello, P.J. and Howarth, P.A. (1996) The visual effects of immersion in four virtual environments. VISERG Internal Report 9604. Dept. of Human Sciences, Loughborough Univ., Leicestershire, LE11 3TU, UK.

DiZio, P. and Lackner, J.R. (1997) Circumventing side effects of immersive virtual environments. Proceeding of the 7th International Conference on Human-Computer Interaction, 24-29 August, San Francisco, CA.

Earnshaw, R.A., Vince, J.A. and Jones, H. (1995) Virtual Reality applications. Academic Press, ISBN 0-1222-7755-4.

Ehrlich, J.A. (1997) Simulator sickness and HMD configuration. Proc. of SPIE Conf. on Telemanipulator & Telepresence. SPIE 3206, pp. 170-8.

Ehrlich, J.A. and Kolasinski, E.M. (1998) A comparison of sickness symptoms between dropout and finishing participants in virtual environment studies. . Proc. of 42nd Human Factors and Ergonomics Society Annual Meeting, 5-9, October, Chicago, USA, pp.1466-70.

Ehrlich, J.A., Singer, M.J. and Allen, R.C. (1998) Relationships between head-shoulder divergences and sickness in a VE. Proc. of 42nd Human Factors Ergonomics Society Annual Meeting, 5-9, October, Chicago, USA, pp.1471-75.

Finch, M. and Howarth, P.A. (1996) A comparison between two methods of controlling movement within a virtual environment. VISERG Internal report 9606. Dept. of Human Sciences, Loughborough Univ., United Kingdom.

Haas M.W. (1984) Visually coupled systems and simulation devices. Journal of Aircraft, 21(8). pp. 639-640.

Howarth, P.A. and Costello, P.J. (1997) The occurrence of virtual simulation sickness symptoms when an HMD was used as a personal viewing system. Display, vol.18, no.2, pp. 107-116.

Griffin, M.J. (1990) Handbook of human vibration. Academic Press Ltd.

Furness, T.A. and Barfield, W (1995) Virtual environments and advanced interface design. New York: Oxford University Press.

Kalawsky, R.S. (1993) The science of virtual reality and virtual environments. Addison-Wesley Publishing Company, ISBN 0-201-63171-7, 318-320.

Kennedy, R.S. and Stanney, K.M. (1997) Aftereffects of virtual environment exposure: psychometric issues. Proc. Of the 7th International Conf. On HCI, 24-29, Aug., San Francisco, CA.

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

Kennedy, R.S., Drexler, J.M. and Berbaum, K.S. (1994) Methodological and measurement issues for identification of engineering features contributing to virtual reality sickness. *Proceedings of the IMAGE VII Conference*, Tucson, Arizona 12-17 June 1994.

Kennedy, R.S., Lanham, S., Drexler, J.M., Massey, C.J. and Lilienthal, M.G. (1995) Cybersickness in several flight simulators and VR devices: a comparison of incidences, symptom profiles, measurement techniques and suggestions for research. *Proc. of the FIVE Conf. London*, pp. 243-251.

Kennedy, R.S., Berbaum, K.S., Dunlap, W.P. and Hettinger, L.J. (1996) Developing automated methods to quantify the visual stimulus for cybersickness. *Proceedings of the 40th Human Factors and Ergonomics Society Annual Meeting*, pp. 1126-1131.

Kolasinski, E.M. (1996) Prediction of simulator sickness in a virtual environment. PhD thesis, Dept. of Psychology, Univ. of Central Florida, Orlando, Florida (UMI Dissertation Service, USA).

Kolasinski, E.M. and Gilson, R.D. (1998) Simulator sickness and related findings in a virtual environment. *Proc. of 42nd Human Factors and Ergonomics Society Annual Meeting*, 5-9, October, Chicago, USA, pp.1511-15.

Kuhl, J., Evans, D., Papelis, Y., Romano, R. and Watson, G. (1995) The Iowa driving simulator: an immersive research environment. *IEEE Computer*. pp.35-41.

Lampton, D.R., Knerr, B.W., Goldberg, S.L., Bliss, J.P., Moshell, J.M. and Blau, B.S. (1994a) The virtual environment performance assessment battery (VEPAB): Development and evaluation. *Presence*, 3(2), pp.145-7.

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

Lamson, R.J. (1997) *Virtual Therapy*. Polytechnic International Press, ISBN 2-553-00631-4, pp.72-94.

Lawther, A. and Griffin, M.J. (1986) The motion of a ship at sea and the consequent motion sickness amongst passengers. *Ergonomics* Vol. 29, pp. 535-552.

Lawther and Griffin (1988) A survey of the occurrence of motion sickness amongst passengers at sea. *Aviation, Space, and Environmental Medicine*, Vol. 59, pp. 399-406.

Lin, F., Hon, C.L. and Su, C.J. (1996) A virtual reality based training system for CNC milling machine operations. *Annual journal of IIE(HK)*, pp.13-16.

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

Reason, J.T and Brand, J.J. (1975) Motion Sickness. Academic Press.

Regan, E.C. (1995) An investigation into nausea and other side-effects of head-coupled immersive virtual reality. Virtual Reality: research, development and applications. Vol. 1, No. 1, pp. 17-32.

Regan, E.C. and Price, K.R. (1993a) Some side-effects of immersion virtual reality. APRE, UKMOD. Report 93RO10.

Regan, E.C. and Price, K.R. (1993b) Subjective views on an immersion virtual reality system and its peripherals. Working paper 16/93, UKMOD.

Regan, E.C. and Price, K.R. (1993c) Some side-effects of immersion virtual reality: the effects of increasing head movements, rapid interaction, and seating subjects. APRE, UKMOD, Report 93RO22.

Rich, C.J. and Braun, C.C. (1996) Assessing the impact of control and sensory compatibility on sickness in virtual environments. Proceedings of Human Factors and Ergonomics Society 40th Annual Meeting, Santa Monica, CA: Human Factors & Ergonomics Society. pp. 1122-1125.

Rod, S. and Pardini, A. (1996) Telepresence and virtual environment applications at Hanford. Nuclear News. January. pp. 34-36.

Salzman, M.C., Dede, C. and Loftin, R.B. (1995) Usability and learning in educational virtual realities. Proceedings of the Human Factors and Ergonomics Society 39th Annual Meeting, Santa Monica, CA, pp. 486-490.

Slater, M., Linakis, V., Usoh, M. and Kooper, R. (1996) Immersion, presence and performance in virtual environments: an experiment with tri-dimensional chess. Proceedings of the ACM Symposium on Virtual Reality Software and Technology, 1-4 July, pp. 163-172.

So, R.H.Y (1994) An investigation of the effects of lags on motion sickness with a head-coupled visual display. Proceeding of the United Kingdom Informal Group Meeting on Human Response to Vibration held at the Institute of Naval Medicine, Alverstoke, Gosport, Hants, PO12 2DL. 19th to 21st September 1994.

So, R.H.Y. and Lo, W.T. (1998) Cybersickness with virtual reality training applications: a claustrophobia phenomenon with Head-Mounted Displays? Proceedings of the First World Congress on Ergonomics for Global Quality and Productivity, 8-11 July, Hong Kong, pp. 209-11.

So, R.H.Y. and Lo, W. T. (1999) Use of 'spatial velocity' to quantify virtual scene movement for the study of cybersickness. Submitted to PRESENCE. Awaiting publication.

So, R.H.Y., Finney, C.M. and Goonetilleke, R.S. (1999) Motion sickness susceptibility and occurrence in Hong Kong Chinese. Contemporary Ergonomics 1999. Taylor & Francis.

Stanney, K.M. and Kennedy, R.S. (1997) Development and testing of a measure of the kinesthetic position sense used to assess the aftereffects from virtual environment exposure. Proceedings of IEEE 1997 Virtual Reality Annual International Symposium, pp. 87-94.

Stanney, K.M. and Kennedy, R.S. (1998) Aftereffects from virtual environment exposure: how long do they last? Proc. of 42nd Human Factors and Ergonomics Society Annual Meeting, 5-9, October, Chicago, USA, pp.1476-80.

Stanney, K.M., Kennedy, R.S., Drexler, J.M. and Harm, D.L. (1999) Motion sickness and proprioceptive aftereffects following virtual environment exposure. Applied Ergonomics, Vol. 30, No. 1, pp. 27-39.

Stern, R.M., Hu, S., Vasey, M.W. and Koch, K.L. (1989) Adaptation tovection-induced symptoms of motion sickness. Aviation, Space, and Environmental Medicine. No.60, pp. 566-572.

Vince, J.A. (1995) Virtual reality systems. Addison-Wesley: London. ISBN 0-201-876876.

Wilson, J.R., Nichols, S. and Haldane, C. (1997) Presence and side effects: complementary or contradictory? Proc. of the HCI'97, San Francisco, pp. 889-892.

List of Figure and Table Captions

Table 1 Summary of experimental studies of cybersickness (excluding studies of simulator sickness in a non-VR environment).

Table 2 ANOVA table of nausea ratings analyzing the effects of subject, exposure duration, and with and without scene oscillations.

Table 3 ANOVA table of nausea ratings obtained with scene oscillations in pitch, yaw, and roll axes (analyzing the effects of subject, exposure duration, and axes of scene oscillations).

Table 4 ANOVA table of Total Sickness Scores analyzing the effects of subject and scene oscillations (with and without).

Table 5 ANOVA table of Total Sickness Scores obtained with scene oscillations in pitch, yaw, and roll axes (analyzing the effects of subject and axes of scene oscillations).

Figure 1 Sample scenes of what the subjects saw on the Head Mounted Display during scene oscillations. The virtual environment contains some buildings, a train station, tracks, cables, and bridges.

Figure 2 Mean nausea ratings with and without scene oscillations as functions of exposure duration (data from 16 subjects, +/- one standard deviation are shown).

Figure 3 Mean nausea ratings with scene oscillations in different axes as functions of exposure duration (data from 16 subjects, +/- one standard deviation are shown).

Figure 4 A simple conceptual model of cybersickness generation.

Figure 5 Mean sickness scores before and after a 20-minute simulation with and without scene oscillation (+/- one standard deviation are shown).

Figures and Tables

Table 1 Summary of experimental studies of cybersickness (excluding studies of simulator sickness in a non-VR environment).

Types of variables	Variables investigated	References
Variables related to "how" visual scene movement is presented ("static" measures of scene motion)	Duration of exposure (including with / without exposure)	Bliss <i>et al.</i> (data from Kennedy and Stanney, 1997); Lampton <i>et al.</i> (1994a,b); Kennedy <i>et al.</i> (1995); Kolasinski and Gilson (1998); Regan and Price (1993a,b,c); Regan (1995); Salzman <i>et al.</i> (1995); So (1994); So and Lo (1998, 1999); Stanney and Kennedy (1997, 1998); Stanney <i>et al.</i> (1999); Wilson <i>et al.</i> (1997)
	Types of VR displays	Costello and Howarth (1996); Howarth and Costello (1997); Lampton <i>et al.</i> (1994); Wilson <i>et al.</i> (1997)
	Display's field-of-view	DiZio and Lackner (1997)
	Display lags	DiZio and Lackner (1997); So (1994)
	Stereoscopic presentation	Ehrlich (1997)
Subject-related variables	Method of navigation	Finch and Howarth (1996); Rich and Braun (1996); Ehrlich (1997); Ehrlich <i>et al.</i> (1998); Kolasinski (1996); Regan & Price (1993b,c); Rich & Braun (1996)
	Age, gender, posture stability	
	Sitting Vs Standing	Regan and Price (1993b)
	Amount of head movement interactions	Regan (1995); So (1994)
Variables related to "what" visual scene movement is presented ("dynamic" measures of scene motion)	Drug treatment	Regan (1995)
	Types of scene background	Slater <i>et al.</i> (1996); Kennedy <i>et al.</i> , 1994
	Quantifying scene movement in a VE	Kennedy <i>et al.</i> (1996); So and Lo, 1999

Table 2 ANOVA table of nausea ratings analyzing the effects of subject, exposure duration, and with and without scene oscillations.

Source	DF	Sum of Squares	Mean Square	F Value	Pr > F
Scene movement (with/without)	1	34.12	34.13	130.0	0.0001
Duration	4	67.34	16.84	64.1	0.0001
Subject	15	17.28	1.15	4.4	0.0001
Scene * Duration	4	9.89	2.47	9.4	0.0001
Scene * Subject	15	9.89	0.66	2.5	0.0023
Duration * Subject	60	20.56	0.34	1.3	0.0973
Error	160	42.00	0.26		
Corrected Total	319	209.42			

Table 3 ANOVA table of nausea ratings obtained with scene oscillations in pitch, yaw, and roll axes (analyzing the effects of subject, exposure duration, and axes of scene oscillations).

Source	DF	Sum of Squares	Mean Square	F Value	Pr > F
Axes movement	2	0.56	0.28	1.6	0.1983
Duration	4	74.81	18.70	109.9	0.0001
Subject	15	21.56	1.44	8.5	0.0001
Axes * Duration	8	1.44	0.18	1.1	0.3967
Axes * Subject	30	19.58	0.65	3.8	0.0001
Duration * Subject	60	22.13	0.37	2.2	0.0002
Error	120	20.43	0.17		
Corrected Total	239	160.50			

Table 4 ANOVA table of Total Sickness Scores analyzing the effects of subject and scene oscillations (with and without).

Source	DF	Sum of Squares	Mean Square	F Value	Pr > F
Scene movement (with/without)	1	3084.59	3084.59	17.3	0.0001
Duration (pre / post)	1	19924.57	19924.57	112.0	0.0001
Subject	15	11538.79	769.25	4.3	0.0001
Scene * Duration	1	2150.92	2150.92	12.1	0.0008
Scene * Subject	15	4205.86	280.39	1.6	0.0997
Duration * Subject	15	7905.51	527.03	3.0	0.0009
Error	79	11292.66	176.45		
Corrected Total	127	62864.54			

Table 5 ANOVA table of Total Sickness Scores obtained with scene oscillations in pitch, yaw, and roll axes (analyzing the effects of subject and axes of scene oscillations).

Source	DF	Sum of Squares	Mean Square	F Value	Pr > F
Axes movement	2	488.69	244.35	1.72	0.1968
Duration	1	21150.56	21150.56	148.62	0.0001
Subject	15	13746.17	916.41	6.44	0.0001
Axes * Duration	2	159.98	79.99	0.56	0.5759
Axes * Subject	30	6374.56	212.49	1.49	0.1390
Duration * Subject	15	9787.68	652.51	4.59	0.0002
Error	30	4269.42	142.31		
Corrected Total	95	55977.06

Figure 1 Sample scenes of what the subjects saw on the Head Mounted Display during scene oscillations. The virtual environment contains some buildings, a train station, tracks, cables, and bridges.

Figure 2 Mean nausea ratings with and without scene oscillations as functions of exposure duration (data from 16 subjects, +/- one standard deviation are shown).

Figure 3 Mean nausea ratings with scene oscillations in different axes as functions of exposure duration (data from 16 subjects, +/- one standard deviation are shown).

Figure 4 A simple conceptual model of cybersickness generation.

Figure 5 Mean sickness scores before and after a 20-minute virtual simulation with and without scene oscillation (+/- one standard deviation are shown).