Effects of Navigation Speed on Motion Sickness Caused by an Immersive Virtual Environment

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This study investigated the effects of navigation speed on the level of motion sickness during and after a 30-min head-steered virtual environment. Root-mean-squares for 8 speeds in the fore-and-aft axis were 3, 4, 6, 8, 10, 24, 30, and 59 m/s. Participants were 96 Chinese men. Both the nausea and vection ratings increased significantly with speeds increasing from 3 m/s to 10 m/s. At speeds exceeding 10 m/s, the ratings stabilized. Navigation speeds were found to significantly affect the onset times of vection and nausea but did not affect their rates of increase with duration of exposure. For the various Simulator Sickness Questionnaire scores, navigation speed had a significant influence on only the oculomotor subscore. Actual or potential applications of this research include the prediction of sickness associated with simulation tours in a virtual environment at different navigation speeds.

INTRODUCTION

Motion sickness associated with exposure to virtual environments (VEs) has been the subject of many studies (see reviews in Stanney, Salvendy, et al., 1998, and Wilson, 1996). This type of sickness has been referred to as a type of vection-induced sickness (Hettinger, Berbaum, Kennedy, Dunlap, & Nolan, 1990) and is called *cybersickness* (McCauley & Sharkey, 1992). In a VE, operators can be exposed to moving scenes with a wide field of view in the absence of appropriate physical motion. This may cause the illusion of self-motion in the opposite direction (referred to as *vection*). Such experiences have been reported to be nauseogenic for participants navigating through a VE (e.g., Cobb, Nichols, Ramsey, & Wilson, 1999; Lo & So, 2001; Regan, 1995; Stanney & Kennedy, 1998).

Because vection and sickness can be generated by watching moving scenes in a VE, the effect of navigation speed on the level of cybersickness becomes an interesting line of research. How fast or slow should an operator navigate through a VE in order to minimize the occurrence of cybersickness? A review of the literature indicates that although the effects of navigation methods have been studied (e.g., Hash & Stanney, 1995: level of control; Howarth & Finch, 1999: head-control vs. manual-control navigation; Regan, 1995: increased head movement and speed of interactions; Rich & Braun, 1996: presence or absence of active control of navigation), we know of no studies that have purposely investigated the effects of navigation speed on cybersickness. The study that comes closest to this objective seems to be Regan (1995), in which participants in one group were instructed to interact with the VEs as fast as they could and members of the other group were free to control their own speed of interaction. Results showed that there was no significant difference in the Simulator Sickness Questionnaire (SSQ; Kennedy, Lane, Berbaum, & Lilienthal, 1993) scores between the two groups. However, the speeds of navigation through the VEs were not measured in that study.

In lieu of studies on the effects of navigation speed on cybersickness, we can review studies

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concerning vection-induced sickness during exposure to moving scenes other than VEs. Hu, Stern, Vasey, and Koch (1989) reported that as the rotating speeds of an optokinetic drum with black and white stripes changed from 15°/s to 90°/s, symptoms of vection-induced sickness increased, peaked, and then declined. The peak in sickness occurred at 60°/s. Muller, Wiest, and Deecke (1990) reported that the time taken for vection to occur shortened as the speed of rotating scene increased from 10°/s to 40°/s. Beyond 40°/s, the time remained similar for speeds up to 200°/s. Muller et al. used three different scene patterns (random dots, stripes, and checkerboard), for which they obtained similar results.

The finding of Muller et al. regarding the onset times of vection with different speeds of moving scene is consistent with those reported in Kennedy, Hettinger, Harm, Ordy, and Dunlap (1996). Kennedy and his colleagues reported that the time taken for vection to occur reduced as the speeds of the rotating drum increased from 20°/s to 130°/s, remained steady at speeds between 130°/s to 160°/s, and increased at speeds between 160°/s to 220°/s. At the speeds of 20°/s and 220°/s, some participants failed to experience the sensation of vection.

The three studies suggest that both vection and its associated sickness symptoms can be significantly affected by the speed of the moving scene. The previous studies investigated only *circular vection* (i.e., vection along a rotational axis). In a VE, as users navigate mainly in the fore-and-aft axis, it is expected that *linear vection* will occur (i.e., vection along a translational axis).

This paper investigates the levels of vection and sickness during and after navigating through a VE at different speeds. The objectives of the experiment were to determine the relationships among navigation speeds, rated levels of vection, and rated levels of cybersickness and to investigate the interacting effects between speed and duration of exposure on nausea and vection ratings.

We proposed two hypotheses: (a) Increasing navigation speed will increase ratings of vection and nausea up to a certain level, beyond which the ratings will stabilize until an upper speed is reached, and then the ratings will decline (based on Hu et al., 1989; Kennedy, Hettinger, et al., 1996; and Muller et al., 1990). (b) The effects of navigation speed and the effects of exposure duration will have a significant interaction. The second hypothesis was based on previous physiological studies of vection-induced sickness. Dichgans and Brandt (1972) reported a convergence of visual and vestibular information, which suggests that watching moving scenes will directly stimulate the vestibular neurons and cause the sensation of vection. Research has also shown that stimulation to the vestibular neurons will trigger responses in parts of the central nervous system that are associated with symptoms of sickness (Muth, Jokerst, Stern, & Koch, 1995; Stern et al., 1985). Following this logic, we hypothesized that the duration as well as the moving speed of visual stimuli will affect the responses of the central nervous system, and, hence, there will be a significant interaction between the effects of navigation speed and the effects of duration of exposure. Readers can refer to Dichgans and Brandt (1978) for a detailed review of physiological research on the generation of vection-induced sickness.

METHODS

Participants

The participants – 96 male Chinese university students and staff between 19 and 38 years of age – were paid HK $50 as compensation for their time. All were consenting volunteers without color blindness and had not been exposed to any VE within the previous 4 weeks.

Apparatus and the VE

A Virtual Research VR4 (Virtual Research Systems, Inc., Aptos, CA) LCD head-mounted display with a 48° × 36° field of view was used, and a Polhemus 3-SPACE (Polhemus, Inc., Colchester, VT) magnetic tracker was mounted on the display to measure head position and orientation at a rate of 30/s. Attention was paid to ensure that the system response lags were similar across all eight navigation speed conditions. The VE was rendered using the dVISE (Division Ltd., PTC, Needham, MA) software running on a Silicon Graphics ONXY

Figure 1. An example view of the virtual environment.

II (Silicon Graphics, Mountain View, CA) workstation. The VE was presented on the head-mounted display in biocular mode. During exposure to the VE, the participants' viewpoint navigated along a predetermined path, and participants could steer their viewpoint using head movements. The VE contained a virtual city with trees, railway tracks, overhead cables, trains, a train station, and skyscrapers (Figure 1). All participants were exposed to the same VE and the same navigation path, but each group of 12 participants was exposed to one of eight different navigation speeds. The path formed a closed loop, and the participants traveled the path more than once, the number of loops depending on the navigation speed.

Experimental Design

Speeds of 3.3, 4.3, 5.9, 7.9, 9.5, 23.6, 29.6, and 59.2 m/s root mean square (*RMS*) in the fore-and-aft axis were investigated in a full factorial between-subject experiment with eight conditions. Each condition was tested on 12 participants. The duration of exposure to the VE was 30 min. The speeds of navigation inside the VE were measured using the viewpoint of the participants as the origin (i.e., a moving origin). The fore-and-aft, lateral, and vertical directions represented the front-and-back, left-and-right, and up-and-down directions relative to the participant (Figure 2). The roll, pitch, and yaw angles represented the angles of rotation about the fore-and-aft, lateral, and vertical axes, respectively.

The eight navigation speeds broken down along six axes are listed in Table 1. Inspection of Table 1 indicates that the navigation movements are dominantly in the fore-and-aft and the yaw axes. As the navigation path was constructed to simulate a normal walking path, it is natural that there were fewer movements in the vertical, lateral, roll, and pitch axes. It should be noted that in the yaw axis, the speeds of pure scene movement introduced by navigation are shown along with the resultant

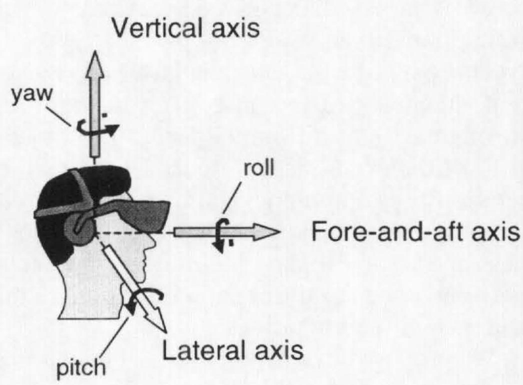

Figure 2. Illustration of the viewer-centered coordinate system used to measure the direction of navigation speed.

TABLE 1: Average Velocities (*RMS*) along Six Axes at the Eight Navigation Speeds Measured Using the Viewer-Centered Coordinate

	Levels of Navigation Speed							
Axes	1	2	3	4	5	6	7	8
Fore and aft (m/s)	3.3	4.3	5.9	7.9	9.5	23.6	29.6	59.2
Lateral (m/s)	1.2	1.6	2.1	2.9	3.4	8.7	10.8	21.5
Vertical (m/s)	0.2	0.3	0.4	0.5	0.6	1.5	1.8	3.7
Roll (°/s)	0.5	0.6	0.8	1.2	1.4	3.5	4.4	8.8
Pitch (°/s)	0.6	0.8	1.1	1.4	1.6	4.2	5.1	10.3
Yaw (°/s)	14.2 *3.8	16.2 *4.9	15.6 *6.8	16.5 *9.1	17.3 *10.9	30.3 *27.2	36.6 *34.1	69.5 *68.1

*Indicates *RMS* velocity of scene movement in the yaw axis after excluding the scene movements resulting from participants' correct head-turning responses.

speeds generated by the combination of head turns (see Procedure section) and navigation (Table 1). The reason for this separation is that the sense of self-motion induced by scene movement caused by a correct head-turning response is a perception of real motion and not vection.

Procedure

Before VE exposure, all participants completed a preexposure Simulator Sickness Questionnaire (SSQ; Kennedy, Lane, et al., 1993). Each participant was then randomly assigned to one of the eight navigation speeds. If a participant reported any moderate symptom of discomfort or sickness in the preexposure SSQ, the participant was asked to rest for 10 min prior to filling in a second preexposure SSQ. Participants sometimes experienced discomfort or sickness as they rushed to the laboratory in order to keep other appointments. Before the experiment, the participants were educated about the difference between vection and perceived speed of the surround scene and were reminded to rate only the level of vection. Kennedy, Hettinger, et al. (1996) reported that participants can reliably separate vection from perceived speed.

During the exposure, participants were asked to turn their heads horizontally to one side (covering about 45° in about 1 s), orally describe what they saw, and turn back to face the front. This was repeated once every 30 s, alternating between left and right, so as to encourage participants to be more involved in the VE. At 5-min intervals, participants were asked to orally rate their symptoms of nausea on a 7-point scale and their sensation of vection on a 4-point scale. The 7-point nausea scale has previously been used in studies of cybersickness (e.g., Lo & So, 2001) and of motion sickness (Woodman & Griffin, 1997).

After the exposure, the participants completed a postexposure SSQ. During the simulation, if a participant reported the maximum rating of 6 on the nausea scale (*moderate nausea, want to stop*), the simulation was terminated and the participant were asked to complete the postexposure SSQ. For those participants, a score of 6 was assigned for the remaining verbal rating reports. The opportunity to terminate the simulation was enforced in order to fulfill the ethical requirements of the Human Subject Experimentation Committee at the Hong Kong University of Science and Technology. Of the 96 participants, 10 terminated the simulation in this way.

RESULTS

Analyses of Nausea and Vection Ratings

Nausea and vection ratings are shown in Figures 3 and 4 as a function of navigation speed and duration of exposure. Inspection of

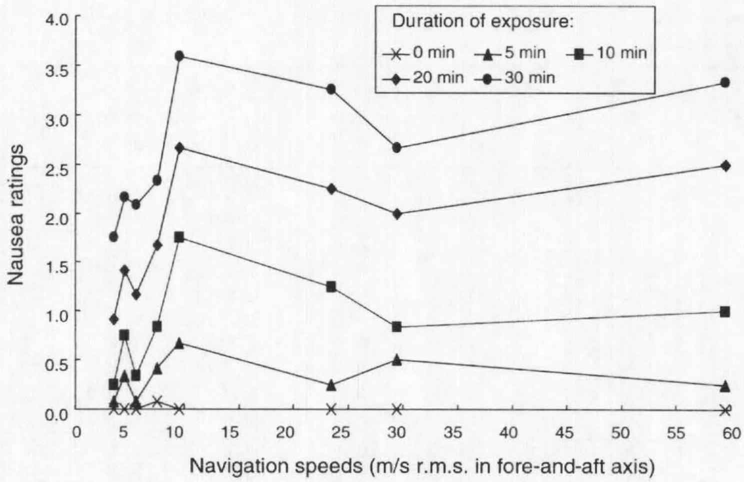

Figure 3. Nausea ratings at 5, 10, 20, and 30 min after the start of the navigation tours of a VE at different scene velocities (as indicated by the RMS scene velocity in the fore-and-aft axis).

the two figures shows that as the duration of exposure increased, both nausea and vection ratings increased. Results of the analysis of variance (ANOVA) indicates that duration had significant effects on both nausea ratings, $F(6, 616) = 52$, $p < .001$, and vection ratings, $F(6, 616) = 55$, $p < .001$. Inspection of Figures 3 and 4 suggests that after 5 min of exposure, both nausea ratings and vection ratings started to increase. The results of Student-Newman-Keuls tests indicate that the increases in nausea and vection ratings with increasing duration were significant after 10 and 5 min, respectively (nausea: $p < .05$; vection: $p < .05$).

Inspection of Figures 3 and 4 show that both vection and nausea ratings can be divided into two regions: (a) at speeds from 3 to 10 m/s, both ratings increased with increasing speeds; (b) beyond 10 m/s, ratings stabilized. This pattern of an increasing region followed by a stabilizing region is partially consistent with the hypothesis that as the speed of scene movement increases, vection and nausea will increase, stabilize, and then decline. Results of Student-Newman-Keuls groupings indicate that vection ratings peaked and became steady at speeds of 8 m/s or more, whereas nausea ratings peaked and became steady at speeds of 10 m/s *RMS* or more ($p < .05$).

A two-factor (Speed × Duration) ANOVA showed that there was no significant interaction between the effects of speed and the effects of duration for either nausea ratings or vection ratings ($p > .95$). Repeated-measure ANOVAs were conducted on the vection and nausea data to test the effects of speed at each time interval (0, 5, 10, 15, 20, 25, and 30 min) and the effect of duration at each speed (3.3, 4.4, 5.9, 7.9, 9.5, 23.6, 29.6, 59.2 m/s). In addition, the effects of speed on the onset times of moderate to strong vection (a rating of 2 or more) and mild to moderate nausea (a rating of 3 or more) were tested using ANOVAs. The onset times were defined as the time of exposure to the VE when the corresponding level of rating was first reported. Results of these ANOVAs are explored in the Discussion section.

Analyses of the SSQ Data

Figure 5 illustrates the changes of the total scores and Figure 6 illustrates the changes of the nausea (N), oculomotor (O), and disorientation (D) subscores as function of fore-and-aft navigation speeds. The calculation procedure of all the SSQ scores is according to Kennedy, Lane, et al. (1993). An ANOVA was conducted to test the main effects of exposure on the SSQ scores of before and after the exposure. Significant increases were found in the total, nausea, oculomotor, and disorientation subscores ($p < .001$). Changes in SSQ scores were

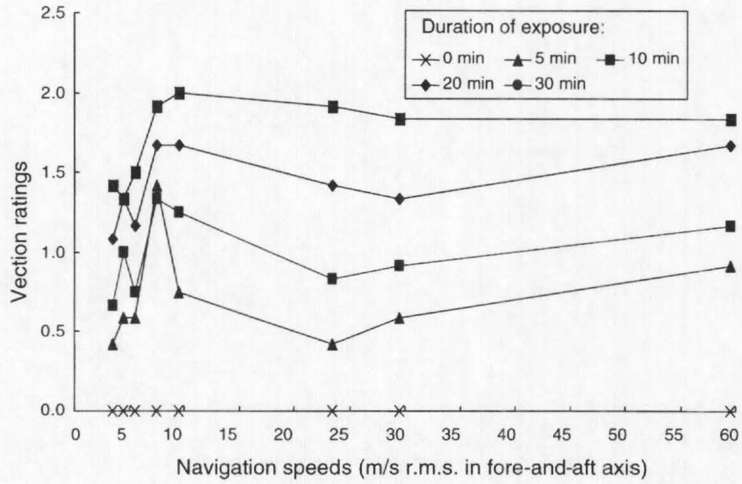

Figure 4. Vection ratings at 5, 10, 20, and 30 min after the start of the navigation tours of a VE at different scene velocities (as indicated by the RMS scene velocity in the fore-and-aft axis).

calculated by subtracting the preexposure scores from the postexposure score (Figures 5 and 6). Subsequent analyses of the effects of speed were conducted on these changes of SSQ scores.

Comparison of Figures 5 and 6 shows that as the fore-and-aft *RMS* speeds increased from 3 to 30 m/s, changes in total score had a pattern similar to those of nausea ratings and vection ratings, increasing with increased speeds up to 10 m/s *RMS*, beyond which the values became steady. However, as the speeds increased from 30 to 59 m/s *RMS*, total score started to increase again, whereas both nausea and vection ratings remained steady. A possible reason for the increase of total score at 59 m/s *RMS* is the increase in disorientation and oculomotor subscores, as can be observed from Figure 6. Results of the ANOVA indicate that the navigation speed had only a marginal significant main effect on the oculomotor subscore ($p < .1$) and did not significantly influence other scores (total score: $p > .1$; nausea: $p > .2$; disorientation: $p > .1$). Possible reasons are discussed in the next section.

Correlation tests showed that the vection rating, the nausea rating, and the postexposure SSQ scores were all significantly correlated with one another ($p < .001$). Besides their expected relationships being consistent with the theory of vection-induced motion sickness, another possible reason may be bias attributable to method variance (e.g., Kemery & Dunlap, 1986). As all the measurements were obtained through questionnaires, the correlation relationships among these measures may have been inflated. Consequently, discussion in this article will focus less on the correlation effects among measurements.

DISCUSSION

In this study, both nausea and vection ratings increased when speeds increased from 3 to 10 m/s. Beyond 10 m/s, the ratings became steady and remained so up to the speed of 59 m/s. This conflicts with the hypothesis that at high speed, vection and nausea ratings will decline. Kennedy, Hettinger, et al. (1996) reported that circular vection reduced when the speed of an optokinetic drum increased beyond 160°/s. In addition, at 220°/s, the black and white stripes inside the drum appeared to fuse together and led to failure of circular vection sensation. In the present study, the "fusing" phenomenon did not occur. At the speed of 59 m/s, all participants were still able to see and describe objects inside the VE as well as to experience vection. The obvious reason is the difference in the speed of scene movement. At a speed of 59 m/s in the fore-and-aft axis, the speed in the yaw axis was 68 m/s, much slower

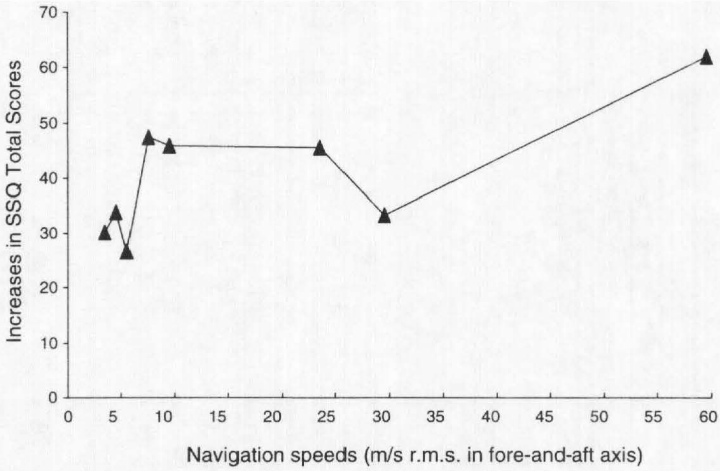

Figure 5. Increases in total sickness severity scores measured by the Simulator Sickness Questionnaire (SSQ) after a 30-min navigation tour of a VE at different scene velocities (as indicated by the RMS scene velocity in the fore-and-aft axis).

than 160 m/s. Other possible reasons include the difference in the visual environment. In a VE, the visual scene is a three-dimensional perception and therefore much more complicated than black and white stripes.

Inspection of Figure 4 indicates that at 5 min after the start of exposure, the mean vection rating obtained at 8 m/s *RMS* were much higher than those at other speeds. Repeated-measures ANOVAs were conducted to investigate the effects of duration at each speed and the effects of speed at each time interval. Results indicate that 5 min after the start of simulation, significant increases in vection ratings were found only at the speed of 8 m/s ($p < .05$). After 10 min, vection ratings significantly increased at all speeds. This suggests that speed significantly affected the onset time of vection sensation, which was less than 5 min at a speed of 8 m/s and between 5 to 10 min at speeds lower or higher than 8 m/s. Results of Student-Newman-Keuls analyses indicate that the mean vection and nausea ratings increased significantly after 5 and 10 min, respectively ($p < .05$). This suggests that on average, the onset of vection sensation occurred earlier than that of nausea. This is consistent with current knowledge on the pathology of vection-induced motion sickness, which suggests that watching moving scenes causes the sensation of vection and triggers responses by the central nervous system that are associated with symptoms of sickness.

The nonsignificant interaction between the effects of navigation speed and the effects of the duration of exposure on both the nausea and vection ratings is somewhat surprising ($p > .9$). It had been hypothesized that there would be a significant interaction between the effects of duration and speed. In other words, it was expected that viewing scene movements at speeds that cause stronger levels of vection and nausea symptoms would increase both symptoms at a higher rate as exposure continued. However, the hypothesized effects did not occur. Inspection of Figures 3 and 4 indicates that (with the exception of vection ratings at 5 min) the curves showing the effects of speed on both vection and nausea ratings at each time interval are approximately parallel.

In order to explain the lack of significant interactions between the effects of speed and duration, one has to look at the results of repeated-measure ANOVAs on the effects of speed at each duration and vice versa. Results of the repeated-measures ANOVAs show that after 15 min of exposure the influence of speed on vection sensation became insignificant, and after 30 min of exposure the influence of speed on nausea ratings became insignificant, even though both nausea and vection ratings continued to increase with increasing duration of

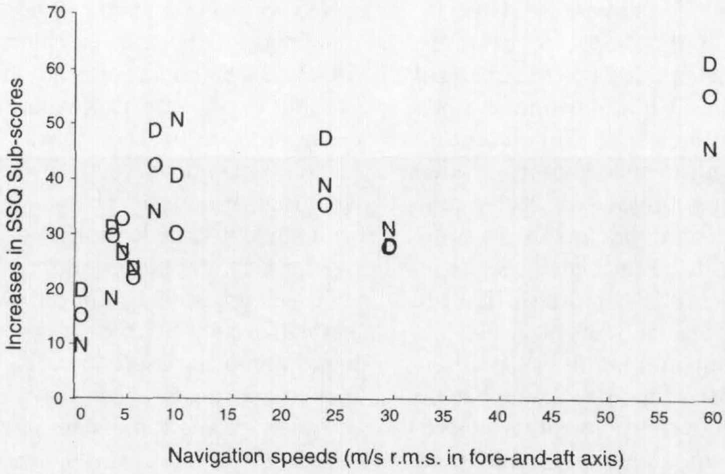

Figure 6. Increases in the nausea (N), disorientation (D), and oculomotor (O) subscores after the navigation tours of a VE at different scene velocities (as indicated by the RMS scene velocity in the fore-&-aft axis).

exposure from 0 to 30 min. These nonlinear effects are consistent with the finding that navigation speed was affecting the onset times of vection and nausea ratings whereas the duration was affecting the intensity levels of vection and nausea ratings. In other words, at the start of exposure, the ratings at some speeds started to increase sooner than at other speeds. Therefore, the effects of speed were significant. However, as duration increased, ratings at all speeds increased, and the increasing effects of duration eventually overshadowed the effect of speed. Further analysis of the rating data indicates that navigation speed significantly affects the onset times of moderate to strong vection (a vection rating of 2 or more) and the onset times of mild to moderate nausea (a nausea rating of 3 or more) ($p < .001$). This supports the idea that navigation speed was affecting the onset times of vection and nausea.

The finding that the effects of navigation speed were overshadowed by the effects of duration toward the end of the exposure provides a possible explanation for the lack of significant effects of speed on most of the SSQ scores. Another possible reason is that at speeds of 8 and 10 m/s, susceptible participants reported earlier onset of vection and nausea, reached the maximum nausea rating ("moderate nausea, want to stop") before 30 min, and had to quit the exposure. This left room for participants exposed to the VE at other speeds to catch up. Out of the 10 participants who had reached the maximum nausea rating before 30 minutes, 5 were exposed to the VE at the speed of 10 m/s. As shown in Figures 3 and 6, both the nausea ratings and the SSQ nausea scores peaked at the speed of 10 m/s. Had the 5 participants who terminated the exposure before 30 min been able to carry on, the mean nausea rating and SSQ nausea score at 10 m/s would have been even higher. Consequently, it can be deduced that the effect of speed on SSQ scores was conservative in this study.

The visual content of a VE can vary greatly from one environment to another. Will the findings of this study be applicable in general or only to the particular VE used in this experiment? We suggest that although the absolute value of speeds (e.g., 10 m/s *RMS* in the fore-and-aft direction) at which the vection and nausea ratings were at their maximum will be specific to this study, the pattern of change will be generally applicable. The consistency of the patterns of changes in vection and sickness ratings with different speeds in this study and those reported in Hu et al. (1989), Kennedy, Hettinger, et al. (1996), and Muth et al. (1995) provides further support for the general applicability of the pattern of changes.

In this study participants perceived movements of spatially contrasted elements in a VE, whereas in studies with an optokinetic drum, participants perceived movements of spatially contrasted black and white stripes (e.g., Hu et al., 1989, 1997; Stern et al., 1985). We acknowledge that unless the densities of the spatially contrasted scenes in a VE and inside an optokinetic drum can be measured and quantified, the effects of navigation speed among studies with different scenes cannot be directly compared. The spatial frequency inside an optokinetic drum can easily be calculated because of its regular pattern, but it is more difficult to measure the average spatial frequencies of a VE.

Kennedy, Berbaum, and Smith (1993), Kennedy, Drexler, and Berbaum (1994), and Kennedy, Berbaum, Dunlap, and Hettinger (1996) developed the first automated method to quantify the visual stimulus for the study of cybersickness. The reported method was referred to as the "human judged kinematics cluster score" (Kennedy, Berbaum, et al., 1996). This score has been shown to correlate with levels of cybersickness. However, as reported by Kennedy and his colleagues, this method involved analyses of videotapes of virtual scenes by human observers and was subjective. So and Lo (2000) reported an automatic and objective method to sample, measure, and calculate a metric to represent the average spatial frequencies (in cycles per degree) of a VE. Using this metric (called *spatial velocity*), the eight navigation velocities in this study can be converted to eight levels of scene movement with units of cycles per second (or cycles × meters/second × degree in translational axes). Future studies on the effects of navigation speed will be combined with measurements of the spatial complexity of the VEs.

This study used only male Chinese participants; future experiments should include female participants. Kolasinski (1995) reported a significantly higher level of cybersickness (SSQ scores) with female participants, and Stern, Hu, Leblanc, and Koch (1993) reported a significantly higher susceptibility to vection-induced motion sickness in Chinese American women than in African American and European American women.

CONCLUSION AND FUTURE WORK

In this study, vection sensation and sickness symptoms increased with increasing navigation speeds from 3m/s to 10m/s *RMS*. Beyond 10m/s *RMS*, both vection and sickness stabilized and remained steady as speeds increased further to 59m/s *RMS*. This is consistent with previous findings on the effects of rotating speed on circular vection. Further, it was found that the mean onset time of vection sensation is earlier than that of nausea. This is, again, consistent with current knowledge that cybersickness is a type of vection-induced motion sickness.

This study has shown that navigation speed can significantly affect levels of vection during the first 5 min of exposure to a VE. When the duration of exposure is longer than 15 min, the effects of speed on vection became insignificant. For nausea, the effects of speed were significant after 10 min into the exposure and became insignificant after 30 min. Because of ethical requirements, participants could terminate the exposure when they passed a moderate level of nausea. This restricted the effects of navigation speeds and possibly caused the effect of speed on the postexposure SSQ scores to be insignificant. It is desirable that future studies seek special approval to raise the allowable level of sickness.

Evidence has been found to suggest that navigation speed will significantly affect the onset times of vection sensation and nausea but will not accelerate their rates of increase with increasing duration. The lack of significant interaction between the effects of duration of exposure and navigation speed indicates that there is no multiplicative effect between the two factors – a useful finding for research on the prediction of severity levels of cybersickness.

In this study, navigation movements were mainly in the fore-and-aft and yaw axes. Future studies to investigate the effects of scene movements in other axes are desirable. In addition, methods to analyze the scene complexity of a virtual environment should be used in future experiments investigating the effects of speed. We acknowledge that all measurements of vection and sickness symptoms in this study were derived from questionnaires; future studies should include objective measurements, such as posture stability tests.

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REFERENCES

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

Dichgans, J., & Brandt, T. (1972). Visual-vestibular interaction and motion perception. *Bibliotheca Ophthalmologica, 82*, 327–338.

Dichgans, J., & Brandt, T. H. (1978). Visual-vestibular interactions: Effects on self-motion perception and postural control. In R. Held, H. Leibowitz, & H. L. Teuber (Eds), *Handbook of sensory physiology* (pp. 755–804). New York: Springer-Verlag.

Hash, P. A. K., & Stanney, K. M. (1995). Control: A primary driver of cybersickness. In A. C. Bittner & P. C. Champney (Eds.), *Advances in industrial ergonomics and safety VII* (pp. 225–229), London: Taylor & Francis.

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

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

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 and Environmental Medicine, 68*, 306–311.

Hu, S., Stern, R. M., Vasey, M. W., & Koch, K. L. (1989). Motion sickness and gastric myelectric activity as a function of speed of rotation of a circular vection drum. *Aviation Space and Environmental Medicine, 60*, 411–414.

Kemery, E. R., & Dunlap, W. P. (1986). Partialling factor scores does not control method variance: A reply to Podsakoff and Todor. *Journal of Management, 12*, 525–544.

Kennedy, R. S., Berbaum, K. S., Dunlap, W. P., & Hettinger, L. J. (1996). Developing automated methods to qualify the visual stimulus for cybersickness. In *Proceedings of the Human Factors and Ergonomics Society 40th Annual Meeting* (pp. 1126–1130). Santa Monica, CA: Human Factors and Ergonomics Society.

Kennedy, R. S., Berbaum, K. S., & Smith, M. G. (1993). Methods for correlating visual scene elements with simulator sickness incidence. In *Proceedings of the Human Factors Society 37th Annual Meeting* (pp. 1252–1256). Santa Monica, CA: Human Factors and Ergonomics Society.

Kennedy, R. S., Drexler, J. M., & Berbaum, K. S. (1994, June). *Methodological and measurement issues for identification of engineering features contributing to virtual reality sickness.* Presented at the IMAGE VII Conference, Tucson, AZ.

Kennedy, R. S., Hettinger, L. J., Harm, D. L., Ordy, J. M., & Dunlap, W. P. (1996). Psychophysical scaling of circular vection (CV) produced by optokinetic (OKN) motion: Individual differences and effects of practice. *Journal of Vestibular Research, 6*, 331–341.

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

Kolasinski, E. M. (1995). *Simulator sickness in virtual environments* (Tech. Report 1027, ADA 295861). Alexandria, VA: U.S. Army Research Institute for the Behavioral and Social Sciences.

Lo, W. T., & So, R. H. Y. (2001). Effects of scene rotational movements on cybersickness. *Applied Ergonomics, 32(1)*, 1–14.

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

Muller, C. H., Wiest, G., & Deecke, L. (1990, June). *Vertically moving visual stimuli and vertical vection – A tool against space motion sickness?* Presented at the 4th European Symposium on Life Sciences Research in Space, Trieste, Italy.

Muth, E. R., Jokerst, M., Stern, R. M., & Koch, K. L. (1995). Effects of dimenhydrinate on gastric tachyarrhythmia and symptoms of vection-induced motion sickness. *Aviation Space and Environmental Medicine, 66*, 1041–1045.

Regan, C. (1995). An investigation into nausea and other side-effects of head-coupled immersive virtual reality. *Virtual Reality, 1*, 17–32.

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

So, R. H. Y., & Lo, W. T. (2000). A metric to quantify virtual scene movement for the study of cybersickness: Definition, implementation, and verification. *Presence, 10*, 193–216

Stanney K. M., & Kennedy, R. S. (1998). Aftereffects from virtual environment exposure: How long do they last? In *Proceedings of the Human Factors and Ergonomics Society 42nd Annual Meeting* (pp. 1476–1480), Santa Monica, CA: Human Factors and Ergonomics Society.

Stanney, K. M., Salvendy, G., Deisinger, J., DiZio, P., Ellis, S., Ellison, J., Fogleman, G., Gallimore, J., Hettinger, L., Kennedy, R., Lackner, J., Lawson, B., Maida, J., Mead, A., Mon-Williams, M., Newman, D., Piantanida, T., Reeves, L., Riedel, O., Singer, M., Stoffregen, T., Wann, J., Welch, R., Wilson, J., Witmer, B. (1998). Aftereffects and sense of presence in virtual environments: Formulation of a research and development agenda. *International Journal of Human-Computer Interaction, 10*, 135–187.

Stern, R. M., Koch, K. L., Leibowiz, H. W., Lindblad, I. M., Shupert, C. L., & Stewart, W. R. (1985). Tachygastria and motion sickness. *Aviation Space and Environmental Medicine, 56*, 1074–1077.

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

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

Woodman, P. D., & Griffin, M. J. (1997). Effect of direction of head movement on motion sickness caused by coriolis stimulation. *Aviation Space and Environmental Medicine, 68*, 93–98.

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