ISOLATING THE EFFECTS OF VECTION AND OPTOKINETIC NYSTAGMUS ON VISUALLY INDUCED MOTION SICKNESS DURING EXPOSURE TO OPTOKINETIC STIMULI

Jennifer T.T. Ji[1*], Richard H.Y. So[1] and Raymond T.F., Cheung[2]

[1] Computational Ergonomics Research Team, Department of Industrial Engineering and Engineering Management, Hong Kong University of Science and Technology, Hong Kong SAR

[2] Department of Medicine, University of Hong Kong, Hong Kong SAR

* Corresponding author: Dr. Jennifer Ji, Email: ieemjtt@gmail.com

ABSTRACT

Objective: This study investigates isolated effects of vection and optokinetic nystagmus (OKN) on visually induced motion sickness (VIMS) provoked by rotating optokinetic drum patterns. **Background:** VIMS was the subject of recent standardization activities (ISO IWA3, 2005) but the effects of OKN have not been studied in the absence of vection. **Method:** Experiment one suppressed OKN by eye fixation and examined VIMS severity (both ordinal and ratio scale) and time spent in saturated vection at four pattern rotating velocities of 0, 2, 14, and 34 degrees per second (dps). Experiment two suppressed vection by adding a peripheral visual field rotating in the opposite direction to the rotating patterns. VIMS severity and OKN slow-phase velocity were studied at four rotating velocities of 0, 30, 60, and 90 dps. **Results:** Results from Experiment one indicated that VIMS severity increased as the pattern velocity increased from 0 dps to 34 dps. Results from Experiment two indicated that as the velocity of the rotating pattern increased, the slow-phase velocity (SPV) of OKN and the severity of VIMS increased and peaked in the 60 dps condition. In both experiments, ratio-scaled nausea data significantly correlated with ordinal-scaled nausea ratings. **Conclusion:** VIMS can still occur in the absence of either vection or OKN. Interestingly, the profile of the summed

results of the two experiments matches nicely with the profile reported by Hu *et al.* (1989) in which neither OKN nor vection were controlled. **Application:** Potential applications include modeling and reduction of VIMS in computer gaming environments.
Keywords: Vection saturation time, Vection velocity rating, OKN slow-phase velocity, Ratio- and ordinal-scaled nausea severity

INTRODUCTION

Visually induced motion sickness (VIMS) is a major ergonomics concern with the use of virtual reality (VR) technology (Stanney *et al.*, 1998). It was reported that after one hour of exposure to a VR environment, 88% of the users experienced various VIMS symptoms, 71% experienced nausea, and nearly 50% had to terminate their exposure pre-maturely (Stanney & Kingdon, 2002). In 2005, concerns about VIMS among viewers of computer games and entertainment prompted the publication of ISO International Workshop Agreement 3 on image safety (ISO, 2005) and, in 2006, the Commission Internationale de l´Eclairage (CIE) commissioned a technical committee, TC1-67, to study the effects of dynamic and stereo visual images on human health.

Viewers exposed to optokinetic stimuli can exhibit vection, optokinetic nystagmus (OKN, Buttner and Buttner-Ennever, 1988), and VIMS (Flanagan *et al.*, 2002; Webb and Griffin, 2002). VIMS is a variant of motion sickness (MS) (Griffin, 1992; Reason, 1978; Hettinger and Ricco, 1992) and sensory rearrangement theory is the most frequently cited theory to explain VIMS occurrence (Reason, 1978). This theory predicts that vection and not OKN is critical for generating VIMS. Hettinger *et al.* (1990) reported that vection, the illusion of self-motion, was a necessary condition for VIMS elicitation. Consequently, VIMS provoked by rotating optokinetic stimuli has been referred to as 'vection-induced' MS (e.g., Stern *et al.*, 1990; Hu *et al.*, 1997; Hu and Stern, 1998). A review of the literature indicates that participants in these studies also exhibited OKN. In 1994, Ebenholtz and his colleagues proposed the extraocular afferent hypothesis to predict that VIMS is caused by abnormal OKN responses. This prediction was supported by Webb and Griffin (2002) who observed that OKN suppression significantly reduces VIMS severity without significant changes in vection perception. As of today, the effects of vection and OKN on VIMS are still the subject of debate.

Although the effect of vection and OKN on VIMS has been studied by several empirical studies (Stern *et al.*, 1990; Webb and Griffin, 2002; Webb and Griffin, 2003; Flanagan *et al.*, 2004), a study examining both the isolated effects of vection and the isolated effects of OKN on VIMS under the same experimental setup could not be found. Hu *et al.* (1989) reported an inverted U-shaped relationship between rotation velocity of optokinetic stimuli and VIMS severity. In their study, both OKN and vection were not suppressed and VIMS severity peaked when the stimuli rotated at 60 degrees per second (dps) in the yaw axis. In this study, we sought to repeat Hu *et al.*'s (1989) study but to isolate the effects of vection and OKN. The specific objectives were to (i) examine the isolated role of vection perception and the isolated role of OKN in VIMS severity under a similar experimental setup; (ii) determine the VIMS response characteristics as functions of the rotating velocity of stimuli in the absence of OKN or vection, and (iii) compare the use of ratio-scaled and ordinal-scaled VIMS severity data. The third objective was prompted by the lack of ratio-scaled VIMS data. A review of the literature indicates that nearly all the previous VIMS studies measured VIMS severity using ordinal scales (e.g., the Simulator Sickness Questionnaire (SSQ) by Kennedy *et al.*, 1993 and the seven-point nausea rating scale by Golding and Kerguelen, 1992; Webb and Griffin, 2002, 2003). One important application of ratio-scaled data is in the development of computational models (Oman, 1982).

In summary, this paper reports results of two experiments. Experiment one examined the effect of the rotating velocity of an optokinetic pattern (pattern velocity) on VIMS severity in the absence of OKN and in the presence of vection. Experiment two examined the effect of pattern velocity on VIMS severity in the absence of vection and in the presence of OKN. Participants in both experiments were exposed to moving image patterns. However, instead of controlling the rotating velocities of the patterns to be the same in the two experiments, the retinal slip velocities of the pattern stimuli were controlled. Retinal slip velocities are the velocities of image projections on the retinas. There were two reasons for controlling the retinal slip velocities in our study: (i) the two-visual system theory suggests that motion perception is initiated when motion-sensitive receptors on the retinas detect the retinal slip of moving images (Leibowitz and Post, 1982); (ii) as the eyes follow a moving image pattern, the retinal slip is reduced. Consequently, we sought to remove the confounding relationship between the presence of OKN and retinal slip velocities.

EXPERIMENT ONE - ISOLATED EFFECTS OF VECTION ON VIMS WITH OKN SUPPRESSION

Objective and Hypothesis

Experiment one considered the relationship between vection and the severity of VIMS in the absence of OKN in viewers watching a wide field-of-view (FOV) optokinetic striped pattern rotating in the yaw direction at different velocities (pattern velocity). We hypothesized that: (i) pattern velocity, in the absence of OKN, will have a significant main effect on the time spent in saturated vection (H1) and on reported VIMS severity (H2) (based on Hu *et al.*, 1989); and (ii) as the pattern velocity increases, VIMS will increase, peak, and reduce (H3) (based on Hu *et al.*, 1989).

Method and Design

Method to suppress and monitor OKN: Eye fixation has been shown to completely suppress OKN (e.g., Brandt *et al.*, 1973; Stern *et al.*, 1990; Webb and Griffin, 2002; Flanagan, *et al.*, 2002). Brandt *et al.* (1973) used an eye fixation point subtending one degree to suppress OKN. To verify whether an eye fixation point of one degree in diameter could completely suppress OKN in this study, a pilot test was conducted under a similar experimental setup as Experiment one. The visual stimulus took the form of an alternating black-and-white striped pattern (cf: Hu *et al.*, 1997) rotating at a speed of 34 dps. Eight participants watched the stimulus without eye fixation for one minute followed by a second minute of exposure with eye fixation. Electrooculogram (EOG) recordings were made using the BIOPAC® EOG amplifier system (EOG100C, BIOPAC® Systems Inc., CA, USA) with the EOG data acquisition and analysis software (AcqKnowledge, BIOPAC®). The EOG data sampling rate was set at 200 samples per second with a low-pass filter set at 35 Hz. Both horizontal and vertical eye movements were monitored and recorded by separate channels. All EOG recordings had clear slow-phase and fast-phase OKN cycles when the participants did not fixate their eyes. When the participants fixated their eyes, the EOG recordings showed no OKN cycles. These results confirmed that OKN could be completely suppressed by an eye fixation of one degree in diameter in Experiment one. This is consistent with the previous findings that OKN can be fully suppressed by eye fixation point at a drum rotation velocity of 60 dps or higher (Flanagan *et al.*, 2002; Webb & Griffin, 2002; Brandt *et al.*, 1973).

Participants: Past studies have shown that gender can influence symptoms of motion sickness (Griffin, 1992) and female Chinese have been shown to be hyper-susceptible to VIMS (Stern *et al.,* 1993). In this study, female Chinese participants were recruited to examine the effects of vection and OKN on VIMS. Sixteen Chinese female university students, aged 22 to 28 years old, participated in Experiment one. All were consenting volunteers who were healthy and free of medication or illness. This experiment was approved by the Human Subject and Research Ethics Committee at the Hong Kong University of Science and Technology. Two participants vomited during their first exposure and decided to quit the experiment before completing all four conditions. The other 14 participants completed all four conditions and their data were used in the data analysis. Their mean motion sickness susceptibility questionnaire (MSSQ) short raw score (Golding, 2006) was 19.5 (SD=12.6), which was significantly higher than the average score of 12.9 (SD=9.9) reported by Golding (2006). This was consistent with the finding by Stern *et al.* (1993) that Chinese females are hyper-susceptible to motion sickness. All participants had uncorrected or corrected visual acuity greater than or equal to 20/20 in both eyes and they were all able to complete a series of line length estimation tests using free modulus estimation methods (Stevens, 1971). Participants were compensated for their time at an hourly rate of HK$50 (about US$7).

Visual stimulus and apparatus: The optokinetic drum used by Hu *et al.* (1989) was reconstructed virtually by a computer. Images of this computer-generated virtual drum were then projected on a circular wide-angle screen (Da-Lite Inc., USA: matt white) via three projectors. Similar to the optokinetic drum used by Hu *et al.* (1989), the virtual drum had 24 pair of black-and-white stripes with uneven widths (a white stripe had an angular width of 9.3 degrees and a black stripe had an angular width of 5.7 degrees). Views from the center of the virtual drum were projected on a 200 degree (horizontal) by 50 degree (vertical) circular screen. The black-and-white striped pattern was presented at a refresh rate of 60 Hz and 1920×480 resolution by a NVIDIA GeForce 7600GT graphics card running on an Intel Core 2TM computer (2.4GHz CPU, 2GB memory). An external hardware, Matrox Triple Head2Go, was used to split the view into three images for the three projectors. Each of the three images had about 6 degrees horizontal overlap with the adjacent images to create a seamless wide-angle rotating image pattern. Gradient image blending programmed by Visual Basic was used to fade the edges formed by image overlapping. Figure 1 shows a participant standing in front of the circular screen. A chin rest was used to fix the head position and participants were required to hold on to a rigid frame with both hands. Full restraint was not used as it might increase levels of claustrophobia and sickness symptoms (Faugloire *et al.*, 2007; Smart *et al.*, 2002). A video camera was used to monitor the participants during the entire exposure period. An OPTEC® 2000 vision tester was used to measure the visual acuity of the participants.

****

Figure 1 about here

****

Experimental design: The only independent variable in Experiment one was the pattern velocity and it had four levels: 0, 2, 14, and 34 degrees per second. We used a within-subject design and a balanced 4$\times$4 Latin square to counterbalance the order of presenting the four conditions to four participants. This design was repeated four times for the 16 participants. To reduce effects of habituation, the time interval between two successive conditions was at least seven days (Regan, 1995). In Hu *et al.* (1989), velocities of 30, 60, and 90 dps were used. Because Hu did not suppress OKNs in his participants, the resulting image velocities on the retinas were much reduced. From the OKN gain data reported by Koenig *et al.* (1978) (0.91, 0.72, and 0.63 for pattern velocities of 30, 60, and 90 dps), the retinal image velocities were estimated to be 2.7, 16.8, and 33.4 dps. Due to the technical limitations of the display system, the closest pattern velocities that could be displayed were 2, 14, and 34 dps. These were the velocity levels used in this experiment. These four conditions of pattern velocity were designed to map the four conditions of retinal slip velocity in Experiment two. The reason for controlling the retinal slip was explained in the Introduction.

Procedure: Before the experiment, all participants completed a series of visual acuity tests, a motion sickness susceptibility survey questionnaire (So *et al.*, 1999) and a MSSQ-Short questionnaire (Golding, 2006). Before the commencement of each condition, participants were requested to complete a line length estimation test to familiarize themselves with the free modulus magnitude estimation method. After that, participants completed a pre-exposure simulator sickness questionnaire (SSQ). If the participants reported any ‘moderate’ symptoms, they would be asked to rest in an air-conditioned room until the symptom had subsided. If the symptom continued after resting for 15 minutes, participants were asked to come back on another day. The participants were assigned to one of the four conditions according to the counter-balanced Latin square and the duration of exposure of each condition was 30 minutes. EOG recordings were taken throughout the entire exposure period. At the end of each 30 minute condition, participants completed a post-exposure SSQ.

At every two minutes during the exposure, participants reported their subjective nausea severity level using both the free modulus magnitude estimation method and the seven-point nausea rating scale (Golding and Kerguelen, 1992; Webb and Griffin, 2003). In conditions other than the 0 dps condition, participants also needed to report any change in the perceived vection velocity using a fixed modulus magnitude estimation method (Stevens, 1971).

The fixed modulus magnitude estimation of vection velocity: To identify an appropriate anchor point for the fixed modulus magnitude estimation of the vection velocity (i.e., the reference ‘100’), participants were exposed to a pre-condition session lasting up to 90 seconds. A break of 5 to 10 minutes was given between each pre-condition session and the main condition. In the pre-condition session, participants were exposed to rotating patterns at the same speed as the up-coming condition. Eight out of the 14 participants reported brief moments of experiencing full vection saturation in all four pre-condition sessions (i.e., a visual illusion that they were rotating while the patterns appeared to be stationary). The participants were asked to remember that experience as the reference point of 100 for the subsequent estimation of vection velocity using the fixed-modulus magnitude estimation method. For the six participants who did not experience full vection saturation in one or more pre-condition sessions, they were educated about the meaning of the 100 reference rating. The reference rating of 100 refers to the experience of self-motion with a similar magnitude to the velocity of the rotating pattern but in the opposite direction. In other words, a rating of 100 was referenced to the sensation of full vection saturation. .

Data analysis: The time spent on saturated vection (i.e., a rating of 100) was measured for each participant in each condition. The nausea ratio scale data collected by the free-modulus magnitude estimation method was transformed by the modulus equalization method (Stevens, 1971). Because the data were not normally distributed, non-parametric statistical tests were used. Friedman two-way ANOVAs and Wilcoxon signed rank tests were used to test the main effects of pattern velocity. Spearman's rank correlation tests were also used. All the individual time series recordings of EOG along the horizontal axis were analyzed to identify valid OKN cycles using Matlab^{TM} codes and confirmed by visual inspection. For all participants in all four conditions, no repetitive OKN cycle was identified. The OKN SPV for all four conditions was therefore zero. This means that OKN was fully suppressed by eye fixation in Experiment one.

Results

Two participants dropped out because they got too sick. As a result, one of the 4x4 Latin square used to balance the order of presentation could not be completed. Results of the Spearman's correlation tests indicated that the order of presentation did not significantly correlate with VIMS severity (Spearman, N=56, nausea ratio-scale: rho=0.037, p=0.789; seven-point nausea rating: rho=0.015, p=0.914; post SSQ-nausea: rho= -0.103, p=0.449) and vection velocity ratings (Spearman's rho= -0.061, N=56, p=0.654).

Consistent with the observations reported in Hu et al. (1989), as the retinal slip velocity increased from 14dps (corresponded to the 60dps drum velocity condition in Hu et al., 1989) to about 34dps (corresponded to the 90dps drum velocity condition in Hu et al., 1989), participants spent less time in saturated vection (Figure 2), although the change was not significant (Friedman, s=3.57, df = 2, p=0.168). This result did not support hypothesis H1.

****

Figure 2 about here

****

Figure 3 shows that as the pattern velocity increased, VIMS severity as measured by the seven-point nausea rating and the nausea ratio scale increased. The post SSQ-nausea sub-scores data also followed a similar trend (Table1). Results of the Friedman ANOVAs indicated that increases in pattern velocity resulted in significant increases in VIMS severity as measured by the nausea ratio scale (Friedman, s= 6.88, df=3, p=0.014), seven-point nausea ratings (Friedman, s=20.12, df=3, p=0.000) and post SSQ-nausea sub-scores (Friedman, s=11.16, df=3, p<0.011). These results support hypothesis H2. Results of the Wilcoxon tests indicated that when the pattern velocity increased from 2 dps to 14 dps, significant increases in both average nausea ratings (Wilcoxon, N=14, z=-2.199, p=0.028) and post SSQ-nausea sub-scores were found (Wilcoxon, N=14, z=-2.135, p=0.033). The nausea ratio scale data in the 14 dps and 34 dps pattern velocity conditions were significantly larger than the nausea ratio data collected in the 0 dps pattern velocity condition (Wilcoxon, N = 14, 0dps v.s. 14dps, z=-2.521, p=0.012; 0dps v.s. 34dps, z=-2.497, p=0.013). The increases of VIMS severity as pattern velocity increased from 14 dps to 34 dps did not support hypothesis H3.

****

Figure 3 about here

****

****

Table 1 about here

****

Correlation analyses indicate significant positive relationships among the ratio-scaled nausea severity ratings (using free magnitude estimation: Stevens, 1971), nausea ratings (seven-point nausea scale: Golding and Kerguelen, 1992) and the post SSQ-nausea scores (Kennedy *et al.* 1993) (Spearman, N=56, nausea ratio scale vs. seven-point nausea rating, rho=0.883, p=0.000; nausea ratio scale vs. post SSQ-nausea, rho=0.794, p=0.000; seven-point nausea rating vs. post SSQ-nausea, rho=0.851, *p*=0.000). These results indicated that ordinal-scaled and ratio-scaled levels of VIMS were consistent.

EXPERIMENT TWO - ISOLATED EFFECTS OF OKN ON VIMS WITH VECTION SUPPRESSION

Objective and Hypotheses

Experiment two studied the relationship between OKN and VIMS severity in the absence of vection while the participants watched patterns rotating at different velocities in the yaw direction. We hypothesized that: (i) pattern velocity, in the absence of vection, will significantly influence OKN slow-phase velocity (SPV) (based on Koenig *et al.*, 1978) (H4a) and VIMS severity (H4b) (based on Hu *et al.*, 1989); (ii) as pattern velocity increases from 0 to 90 dps, VIMS severity will peak, increase, and reduce (H5) and (iii) OKN slow-phase velocity (SPV) will be significantly correlated with VIMS severity (H6) (based on Webb & Griffin, 2002; 2003). Hypothesis H5 was based upon Hu *et al.* (1989) who reported that VIMS severity peaked when participants were exposed to patterns rotating at 60 dps in the presence of both OKN and vection;

Method and Design

Method to suppress and monitor vection: Brandt *et al.* (1973) reported that when viewing a central and peripheral striped pattern rotating in the yaw axis but in opposite directions, viewers experienced OKN without vection. The rationale was that while OKN is stimulated by the central rotating patterns, vection is stimulated by both the central and peripheral rotating patterns. Brandt and his colleagues reported that if the central and peripheral patterns are rotating in opposite directions, OKN will follow the central rotating patterns while vection can be completely suppressed when the field-of-view of the central rotating pattern is about 100 degrees in diameter. Inspired by the finding of Brandt *et al.* (1973), we designed a central and peripheral striped pattern rotating in opposite directions at the same speed (Figure 4b). A pilot test was conducted to determine the size of the central visual field needed to suppress vection in each pattern velocity condition. Participants were the same as those in Experiment two. The horizontal field-of-view of the central patterns was varied from 10 degrees to 180 degrees in 10-degree steps. The maximum vertical size of the central stimulus was 50 degrees, limited by the screen size. Each participant was exposed to patterns of each size rotating at four different velocities: 15 dps, 30 dps, 60 dps, and 90 dps. In total, each participant was exposed to 64 different trials (18 sizes x 4 velocities). During each trial, the participants were requested to report if vection was experienced and the direction of the perceived self-rotation. If no vection was perceived continuously for 90 seconds, the trial was terminated. There was a three-minute break between each trial. The ranges of stimuli sizes at which each participant reported no vection were recorded and the lower limits of the ranges were used as their personalized sizes of the central visual field in Experiment two.

****

Figure 4 about here

****

Participants: Sixteen Chinese female university students, aged between 21 to 30 years old, were recruited to participate in Experiment two. Two of them also participated in Experiment one, with at least seven days between the two experiments. One participant, not the same person in Experiment one, vomited after exposure to one condition and decided to quit. Another participant reported a very high level of nausea even for the condition of 0 dps (i.e., stationary stimuli). After seeking medical advice and consulting Prof. Graham Harding (an expert in photosensitive epileptic seizure (PES), Harding and Harding, 2007), we concluded that the person was not likely to have experienced PES related symptoms but that it was prudent to relieve her from participating in the experiment. The remaining 14 participants completed all four sessions and their data were used in the data analysis. Their mean MSSQ-short raw score was 14.6 (SD = 7.6) statistically no different from 12.9 (SD = 9.9) reported by Golding (2006). All participants had corrected or uncorrected visual acuity of 20/20 or better for both eyes and were able to complete a series of line length estimation tests using the free modulus magnitude estimation method (Stevens, 1971).

Visual stimulus and apparatus: The visual stimulus consisted of a central rotating striped pattern with personalized FOVs and a peripheral striped pattern rotating in the opposite direction at the same constant speed along the earth-vertical axis (Brandt *et al.*, 1973). The horizontal size of the central visual field was personalized to each participant (ranging from 100 degrees to 180 degrees). Illustrations of visual stimuli used in Experiments one and two are shown in Figure 4. A chin rest was used to constrain head movements. Experiment two used the same apparatus as in Experiment one.

Experimental design: Experiment two had four conditions to study the effects of the four rotating velocities: 0, 30, 60, and 90 dps. The three non-zero velocities were the same as those used in Hu *et al.* (1989) and were expected to produce image velocities on the participants' retinas similar to the four conditions used in Experiment one (see Experiment one). Each condition lasted 30 minutes. Experiment two also used a within-subject design and a balanced 4×4 Latin square to balance the order of presentation. To minimize effects of habituation, the time interval between two conditions for the same participant was at least seven days (Regan, 1995).

Procedure: Before the experiment, participants completed a series of line length estimation tests, a visual acuity test, the motion sickness susceptibility survey and the MSSQ-short questionnaire. Similar to Experiment one, participants completed a pre-exposure SSQ and if anyone reported any 'moderate' symptoms, the participant was asked to rest in an air-conditioned room until her symptoms had subsided. If symptoms persisted after 15 minutes of resting, participants were asked to come back on another day. EOG calibration runs were conducted before the start of the exposure. During the 30-minute exposure, participants were requested to report subjective nausea severity using free modulus magnitude estimation and the seven-point nausea rating scale. Unlike in Experiment one, they were not asked to estimate the vection velocity. Instead, they were asked to rate the vection intensity on a four-point vection scale (Webb and Griffin, 2002) every two minutes. Participants completed a post-exposure SSQ after exposure.

Data analysis: EOG recordings were used to calculate SPVs of the OKNs. To transform the unit of raw EOG data from Volts (V) into degrees, an individualized mapping constant was calculated from EOG records of six calibrated eye movements.

Since the distributions of SPV data do not follow normal distributions, non-parametric tests are used to analyze the data. Similar to Experiment one, recordings of EOG were analyzed by Matlab™ codes to identify cycles of OKNs and to calculate the SPVs.

Results

None of the 14 participants reported any non-zero vection intensity rating over the entire exposure period of the 60 dps and 90 dps conditions. This means that vection perception was fully suppressed by Brandt's method. In conditions where the patterns were rotating at 30 dps, vection perception was fully suppressed in all 14 participants for up to 18 minutes of exposure. Two participants reported a rating of 1 (intermittent vection) at 20 minutes and 22 minutes after the start of the stimulus. Results of the Spearman's correlation test indicate that the order of presentation did not have significant correlation with VIMS severity (Spearman, N = 56, nausea ratio scale: rho = -0.076, $p = 0.579$; seven-point nausea rating: rho = -0.187, $p = 0.168$; post SSQ-nausea: rho = -0.168, $p = 0.216$) and OKN SPV (Spearman's rho = -0.023, N=56, $p = 0.864$).

Results of the Friedman ANOVAs indicate that pattern velocity had a significant main effect on OKN SPV (Friedman, s = 26.23, df=3, p=0.000). This supported hypothesis H4a. Consistent with Koenig *et al.* (1978), the results of the Wilcoxon tests indicated that when the pattern velocity increased from 0 dps to 30 dps and from 30 dps to 60 dps, significant increases in OKN SPV were found (Wilcoxon, N=14, 0dps vs. 30dps:z=-3.301, $p = 0.001$; 30dps vs. 60dps: z = -2.229, $p = 0.026$). When pattern velocity was at 90 dps, although the median OKN SPV reduced, the reduced SPV was not significantly different from that reported at 30 dps and 60 dps (Wilcoxon, N=14, 60dps v.s. 90dps, z = -0.91, $p = 0.363$; 30dps v.s. 90dps, z=-1.726, $p = 0.084$, Figure 5).

****

Figure 5 about here

****

Figure 6 illustrates the effects of pattern velocity on the ratio-scaled VIMS severity and ordinal-scaled nausea ratings. The figure indicates that VIMS severity increases, peaks, and reduces as the pattern velocity increases. Friedman ANOVAs indicate that these changes were significant in the ratio-scaled VIMS severity ratings (Friedman, s=8.35, df=3, p = 0.039), the ordinal-scaled nausea ratings (Friedman, s=20.89, df=3, p=0.000), and the post SSQ-nausea scores (Friedman, s= 8.07, df=3, p=0.045, Table 1). These results supported hypothesis H4b. When the pattern velocity was at 60 dps, both the ratio-scaled VIMS severity and the ordinal-scaled nausea ratings had the highest values (Figure 6) and these values are significantly greater than their corresponding values when the velocity was at 0 dps (Wilcoxon, N=14, nausea ratio scale: z=-2.524, p = 0.012; seven-point nausea rating: z = -2.994, p =0.003). When the pattern velocity was at 90 dps, both ratio-scaled VIMS severity and post SSQ-nausea scores were not significantly different from those reported in the 0 dps condition (Wilcoxon, N=14, nausea ratio scale: z = -1.992, p=0.05; post SSQ-nausea score: z = -1.933, p=0.053). Results from the Wilcoxon tests supported hypothesis H5. Consistent with the findings of Webb and Griffin (2002, 2003), average OKN velocities were significantly correlated with average VIMS severity measured by the seven-point nausea rating (Spearman's rho=0.4, N=56, p=0.000) and the nausea ratio scale data (Spearman's rho=0.31, N=56, p=0.02). These results supported hypothesis H6.

****

Figure 6 about here

****

Results of the Spearman's correlation test indicated that the ratio-scaled VIMS severity data, the ordinal-scaled nausea ratings, and the post SSQ-nausea sub-scores were significantly correlated with each other (Spearman, N=56, nausea ratio scale vs. seven-point nausea rating: rho=0.858, p=0.000; nausea ratio scale vs. post SSQ-nausea: rho = 0.759, p=0.000; seven-point nausea rating: rho = 0.898, p=0.000). This result suggested that using ratio-scaled and ordinal-scaled methods to assess symptoms of VIMS can result in correlated findings.

In this experiment, the median OKN gains calculated from the EOG recordings were 0.93, 0.8, and 0.4 for the three conditions with pattern velocities of 30, 60, and 90 dps, respectively. The trend of reducing OKN gains with increasing pattern velocity was consistent with Koenig *et al.* (1978) who reported OKN gains of 0.91, 0.72, and 0.63 when viewers were watching stimuli rotating at 30, 60, 90 dps.

DISCUSSION

The isolated effect of vection on VIMS

Modern VIMS theories suggest that there are three factors that are potentially the primary causes of VIMS: (i) vection (sensory rearrangement theory: Reason, 1978), (ii) OKN (extra-ocular afferent hypothesis: Ebenholtz *et al.* 1994), and (iii) postural instability (postural instability theory: Riccio and Stoffregen, 1991). Among these three factors, vection was the only factor that was not purposely controlled or suppressed in Experiment one. In fact, vection was purposely stimulated in Experiment one. OKNs were completely suppressed by eye fixation as confirmed by the EOG recordings. Head movements were constrained by a chin rest. Unfortunately, head position was not measured. A post-hoc test indicated that a head sway movement that is two degrees in amplitude can cause an observable and consistent pattern in EOG recordings. Examination of the EOG recordings indicated no evidence of such a pattern among the participants. Consequently, we are confident that the participants did not move their heads by more than two degrees in the first experiment. We do acknowledge that body movement was not measured, however.

Results of experiment one indicated that, in the presence of vection and in the absence of OKN, VIMS severity increased as the pattern velocity increased from 0dps to 2dps, 14dps, and 34dps. However, the averaged times spent in saturated vection were not significantly affected by the changes of pattern velocity from 2dps to 14dps and 34dps. The observed decoupling between the increases in VIMS severity and the changes in time spent in saturated vection is consistent with Flanagan *et al.* (2002) but appeared to be contradictive to the findings in Kennedy *et al*. (1996) and Hettinger *et al*. (1990). Further investigations revealed that different vection measurements were used in the latter two studies. Hettinger et al. (1990) separated subjects into a “vection” group and a “no vection” group and reported a higher VIMS severity in “vection” group. Kennedy et al. (1996) measured vection velocity and reported that vection velocity monotonically increased along with the increase of pattern velocity. In experiment one, times spent in saturated vection were measured. Since the absence of both vection and OKN produced near zero levels of VIMS severity among the participants, the authors would suggest that while the presence vection alone can significantly increase VIMS severity, the level of sickness severity will also depend on the retinal slip velocity of the moving patterns.

Since body posture was not measured in this study, we cannot rule out possible interactions between postural instability and reported sickness. However, all things equal, the main treatments in the two experiments were still the moving stimuli.

The isolated effect of OKN on VIMS

In Experiment two, vection was suppressed by a visual stimulus with central and peripheral visual fields rotating at the same speed but in opposite directions. Head movements were constrained by a chin rest. Since head sways were not measured in this study, we cannot rule out possible interactions between postural instability and reported sickness. However, all things equal, the main treatments in Experiment two were the speed of the moving stimuli and associated OKNs. Results of Experiment two indicate that as the pattern velocities increased from 0 dps to 30, 60, and 90 dps, VIMS severity increased, peaked, and reduced. These effects of pattern velocity on VIMS severity reported in Experiment two are different from the monotonic increasing patterns reported in Experiment one. The OKN slow-phase velocity (SPV) calculated from the EOG recordings in Experiment two had median values of 27.9, 47.8, and 35.5 dps for the conditions with pattern velocities of 30, 60, and 90 dps, respectively. Since both the VIMS severity and OKN SPV peaked under the same condition, this suggests that OKN SPV may influence levels of VIMS. Indeed, the correlations between OKN SPV and VIMS severity were significant (Spearman, $p<0.05$). We argue that OKN can also be a co-variant of VIMS severity.

The role of vection and OKN in generating symptoms of VIMS

In this study, both the presence of retinal slip without OKN and the presence of retinal slip without vection were found to influence both ratio-scaled and ordinal-scaled ratings of nausea significantly. Interestingly, the profile of the changes in VIMS severity with increasing retinal slip velocity in the presence of both OKN and vection matches nicely with the profile of the sum of the changes in VIMS severity reported in Experiments one and two (Figure 7c). This suggests that both OKN and vection are related to the generation of VIMS. It can be observed in Figures 7a and 7b that when images were moving at low retinal slip velocities (about 2 dps), higher nausea levels were generated in the presence of OKN than in the presence of vection. When images were moving at higher retinal slip velocities (about 34 dps), lower nausea levels were generated in the presence of OKN than in the presence of vection. Further studies to investigate the reasons are desirable. Findings from the two experiments demonstrate that VIMS can occur in the presence of vection without OKN and also in the presence of OKN without vection. This implies that neither OKN nor vection is a necessary condition for VIMS to occur. This finding disagrees with Hettinger and Ricco's (1990) claim that vection is necessary for VIMS.

****

Figure 7 about here

****

Figure 7 indicates that as the retinal velocity increased from 0 dps to about 12.2 or 14 dps, symptoms of VIMS increased significantly regardless of the absence of OKN or vection. However, when the retinal velocity increased from 12.2 or 14 dps to about 34 or 48.6 dps, respectively, VIMS symptoms continued to increase in the absence of OKN but they reduced in the absence of vection, although both changes were not statistically significant. Under conditions when the retinal velocities were about 34 or 48.6 dps, the presence of vection without OKN led to significantly higher VIMS severity measured on the ratio scale than did the presence of OKN without vection (Mann-Whitney test, $N=14$, $W=261$, $p= 0.0059$). This suggests that the presence of vection was associated with more severe VIMS than was the presence of OKN when participants watched stimuli that were moving at about 40 dps across the retina

Nausea ratio scale and ordinal scale

In this study, a nausea ratio scale and a seven-point nausea rating scale were used to measure VIMS simultaneously. The significant correlation between VIMS severity measured by the nausea ratio scale and the seven-point nausea rating scale is an important finding. The data collected on the seven-point nausea rating scale gave a meaning to the ratio-scaled nausea number. We acknowledge that one possible reason for the correlation between the ordinal and ratio VIMS ratings may be the deliberate cognitive action of the participants.

Potential applications of the findings

Studying the isolated effects of OKN and vection on VIMS can help to identify effective ways to reduce VIMS. For example, if either the absence of OKN or the absence of vection can prevent the occurrence of VIMS, then solutions to reduce VIMS can focus on the reduction of the appropriate factors. Unfortunately, the findings of the two experiments indicate that neither OKN nor vection is a necessary condition for VIMS to occur.

In this study, OKN slow-phase velocity, VIMS severity, and vection velocity (relative to the pattern velocity) were measured using ratio scale methods. This enabled the development of mathematical models to simulate VIMS generation (e.g., Oman, 1982). Currently, the empirical ratio scale data reported in this paper are being used to verify a computational model simulating VIMS reported from viewers of an optokinetic drum rotating along the earth-vertical axis (Ji *et al.*, 2007). We hope that as computational models to predict VIMS become more and more accurate, they will lead to the development of a system that can predict the probability of VIMS in users playing newly developed computer games. This model could also be included in future standards of image safety (e.g., ISO, 2005).

CONCLUSION, LIMITATIONS AND FUTURE WORK

This study successfully applied Brandt *et al.'s* (1973) method to suppress vection perception in fourteen participants watching rotating scenes at 30, 60, and 90 degrees per second.

OKN gains as functions of the rotating scene velocity reported by Koenig *et al.* (1978) are confirmed.

Image motion projected on the retina in the presence of vection and the absence of OKN can significantly increased the severity of VIMS. As the velocity of the images projected on the retina increased from 0 to 2, 14, and 34 degrees per second, the severity of VIMS significantly increased,

Image motion projected on the retina in the presence of OKN and the absence of vection can also significantly increased the severity of VIMS. As the velocity of the images projected on the retina increased from 0, to 2.1, 12.2, and 48.6 degrees per second, both the OKN slow-phase velocity and the severity of VIMS significantly increased, peaked, and reduced.

Ratio-scaled nausea data have been found to be significantly correlated with ordinal-scaled nausea data. The collection of both ratio- and ordinal-scaled data enabled the future development of mathematical models of VIMS generation.

Future studies to examine the effects of retinal slip on VIMS in the presence of both OKN and vection are desirable. We recommended the measured of absolute perceived vection velocities in future studies because it comprises the presence of vection and the effects of retinal slips. Brandt *et al.* (1973) reported that human subjects can reliably reported perceived vection velocity.

We acknowledge that only female Chinese participants were used in this study and that they have been reported to be hyper-susceptible to motion sickness (Stern *et al.,* 1993). We would also like to point out that two out of 16 participants dropped out from the study because they got too sick to participate. Their data have been excluded in the analyses because they did not participate in all the conditions.

ACKNOWLEDGEMENT

This research was supported by the Hong Kong Research Grants Council through Earmarked Competitive Grants HKUST6128/03E and HKUST619706. The authors thank Mr. Denil Chan and Mr. Eric Chow for their technical support.

REFERENCES

Bonato F., Bubka A., and Alfieri L. (2004). Display color affects motion sickness symptoms in an optokinetic drum. Aviat Space Environ Med, 75, 306-11.

Brandt, T., Dichgans, J., and Koenig, E. (1973). Differential effects of central versus peripheral vision on egocentric and exocentric motion perception. Exp. Brain Res, 16, 476-491.

Buttner, U. and Buttner-Ennever, J.A. (1988). Present concepts of oculomotor organization. In: chapter 1 in Neuroanatomy of the oculomotor system, Elsevier, Amsterdam. New York: Oxford.

Ebenholtz, S.M., Cohen, M.M., and Linder,B.J. (1994). The possible role of nystagmus in motion sickness: a hypothesis. Aviat. Space Environ Med, 65, 1032-1035.

Flanagan, M.B., May, J.G., and Dobie, T.G. (2002). Optokinetic nystagmus, vection, and motion sickness. Aviation, space and environmental medicine, 73, 1067-73.

Flanagan M.B., May J.G., and Dobie T.G. (2004). The role of vection, eye movements and postural instability in the etiology of motion sickness. J Vestib Res., 14, 335-46.

Fletcher, W.A., Hain, T.C. and Zee, D.S.(1990). Optokinetic nystagmus and afternystagmus in human beings: relationship to nonlinear processing of information about retinal slip. Exp Brain Res, 81:41-52.

Golding, J. (2006). Predicting individual differences in motion sickness susceptibility by questionnaire. Personality and Individual Differences, 41, 237–248.

Golding, J. and Kerguelen, M. (1992). A comparison of the nauseogenic potential of low-frequency vertical versus horizontal linear oscillation. Aviation, Space, and Environmental Medicine, 63, 491-497.

Griffin, M.J. (1992). Handbook of Human Vibration. Academic Press.

Harding, G.F.A. and Harding, P.F. (2007). Photosensitive epilepsy and image safety. Proceedings of The First International Symposium on Visually Induced Motion Sickness. Fatigue, and Photosensitive Epileptic Seizures (VIMS2007), Dec 10-11, 2007 - Hong Kong.

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

Hettinger, L.J. and Ricco, G.E. (1992). Visually induced motion sickness in virtual environments. Presence, 1,306-310.

Hu, S., Davis, M.S., Klose, A.H., Zabinsky, E.M., Meux, S.P., and Jacobsen, H.A. (1997). Effects of spatial frequency of a vertically striped rotating drum on vection-induced motion sickness. Aviat. Space Environ Med, 68, 306-311.

Hu, S., Stern R.M., Vasey, M.W., and Koch, K.L. (1989). Motion sickness and gastric myoelectric activity as a function of speed of rotation of a circular vection drum. Aerospace Medical Association, 60, 411-414.

Hu, S. and Stern, R.M. (1998). Optokinetic nystagmus correlates with severity of vection-induced motion sickness and gastric tachyarrhythmia. Aviat. Space Environ Med., 69, 1162-1165.

ISO (2005) ISO International Workshop Agreement-IWA3 Image Safety - reducing the incidence of undesirable biomedical effects caused by visual image sequences. IWA 3:2005(E). ISO copyright office, Case postale 56, CH-1211 Geneva 20.

Ji, J.T.T., Chow E., Lor F., So R.H.Y., Cheung R., Stanney K., and Howarth P.A.(2007). A Biologically Inspired Computational Model Relating Vection and Visually Induced Motion Sickness: Individual Differences and Sensitivity Analysis. Proceedings of The First International Symposium on Visually Induced Motion Sickness, Fatigue, and Photosensitive Epileptic Seizures (VIMS2007), Dec 10-11, 2007 - Hong Kong.

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

Kennedy R.S., Hettinger L.J., Harm D.L., Ordy J.M., and Dunlap W.P. (1996). Psychophysical scaling of circular vection (CV) produced by optokinetic (OKN) motion: individual differences and effects of practice. J Vestib. Res., 6, 331-341.

Koenig, E.J., Allumm, J.H.K. and Dichigans, J. (1978). Visual-vestibular interaction upon nystagmus slow phase velocity in man, Acta Otolaryngol, 85, 397-410.

Leibowitz, H. W. and Post, R. B. (1982). The two modes of processing concept and some implications. In J. Beck (Ed.), Organization and representation in perception, 343-363. Hillsdale, NJ: Erlbaum.

Oman, C.M. (1982) A heuristic mathematical model for the dynamic of sensory conflict and motion sickness. Acta Otolaryngol Supplementum, 392:5-44

Reason, J.T. (1978). Motion sickness adaptation: a neural mismatch model. J. R. Soc. Med, 71, 819-829.

Regan, C.E. (1995) An investigation into Nausea and other side-effects of head-coupled immersive virtual reality. Virtual Reality, Vol. 1 No.1, 1995,

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

Schmid R., Zambarbieri D., and Sardi R. (1979). A mathematical model of the optokinetic reflex. Biol Cybern., 34, 215-25.

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

Stanney, K.M., Salvendy,G., Desisinger, J., Dizio, P., Ellis, S., Ellison, J., Fogleman, G., Gallimore, J., Singer, M., Hettinger, L., Kennedy, R., Lackner, J., Lawson, B., Maida, J., Mead, A., Mon-Williams, M., Newman, D., Piantanida, T., Reeves, L., Riedel, O., 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.

Stanney, K.M. & Kingdon, K.S. (2002). Dropouts and aftereffects: examining general accessibility to virtual environment technology. Proceedings of the Human Factors and Ergonomics Society 46th annual meeting.

Stern, R.M., Hu, S., Anderson, R.B., Leibowitz, H.W. and Koch, K.L. (1990). The effects of fixation and restricted visual field on vection-induced motion sickness. Aviat Space Environ Med, 61, 712-715.

Stern, R.M., Hu, S., LeBlanc, R., and Koch, KL. (1993) Chinese hyper-susceptibility to vection-induced motion sickness, Aviat Space Environ Med, 64:827-830.

Stevens, S.S. (1957). On the psychophysical law. Psychol Rev, 64, 153-181.

Webb, N.A. and Griffin, M.J. (2002). Optokinetic stimuli: motion sickness, visual acuity, and eye movements. Aviat Space Environ Med, 73, 351-358.

Webb, N.A. and Griffin, M.J. (2003). Eye movements, vection and motion sickness with foveal and peripheral vision. Aviat Space Environ Med, 74, 622-625.

List of Figure Captions

Figure 1. A subject standing in front of the rotating striped pattern used in Experiment one. The red arrow is added to indicate the direction of pattern rotation. The head of the subject was fixed by a chin rest. Participants were required to hold on to self-made rigid brackets with both hands during the entire exposure period.

Figure 2. A scatter plot of time spent in saturated vection of 14 participants when viewing black-and-white striped patterns rotating at 2, 14, and 34 degrees per second in the yaw axis. Participants fixed their eyes to eliminate OKN. The solid line connects the medians of three pattern velocity conditions.

Figure 3. Ratio-scaled VIMS severity (□) and ordinal-scaled nausea ratings (●) recorded at the end of 30-minute exposures to rotating black-and-white patterns at 0, 2, 4, and 14 degrees per second. Participants fixed their eyes to eliminate OKN. Means and standard errors are shown.

Figure 4. Illustrations of visual stimuli used in Experiments one and two. (a) Alternate black-and-white striped patterns with an eye fixation point to eliminate OKN in viewers; (b) central and peripheral striped patterns rotating in opposite directions to reduce perceived vection in viewers. The size of the central pattern was personalized.

Figure 5. A scatter plot of OKN slow-phase velocities (averaged over 30 minutes) of 14 participants when viewing black-and-white striped patterns rotating at 0, 30, 60, and 90 degrees per second in the yaw axis. A peripheral striped pattern rotating in the opposite direction of the central striped pattern at the same speed was used to suppress vection. The solid line connects the medians of four pattern velocity conditions.

Figure 6. Ratio-scaled VIMS severity (□) and ordinal-scaled nausea ratings (●) recorded at the end of 30-minute exposures to rotating black-and-white patterns at 0, 30, 60, and 90 degrees per second. Perceived vection in participants was suppressed. Means and standard errors are shown.

Figure 7. A diagram illustrating that VIMS severity caused by image movements on the retina in the presence of both vection and OKN (as reported by Hu *et al.*, 1989) (7c) can be observed as a combination of similar effects reported in Experiment one without OKN (7a) and Experiment two without vection (7b). Figure 7c is replotted from Hu *et al.* (1989) and the levels of image movement velocity (retinal slip velocity) were calculated using the measured OKN gain.

Table 1. Post SSQ-nausea sub-scores (means and standard errors) collected in Experiments one and two. The rotating velocity of the stimuli and the retinal slip velocities are also shown.

Biographies

Dr. Jennifer T. T. Ji, Computational Ergonomics Research Team, Department of Industrial Engineering and Logistics Management, the Hong Kong University of Science and Technology (HKUST), Hong Kong SAR. Dr. Ji obtained her PhD in Human Factors Engineering from HKUST in 2008. She is now working in Singapore as a Supply Chain Analyst.

Dr. Richard H.Y. So, Associate Professor, Computational Ergonomics Research Team, Department of Industrial Engineering and Logistics Management, the Hong Kong University of Science and Technology (HKUST), Hong Kong SAR. Dr. So obtained his PhD in Human Factors Engineering from University of Southampton in 1995. He is a registered member of the Ergonomics Society and a Council Member of the Hong Kong Ergonomics Society. He served on the drafting committee of ISO IWA3 and CIE TC1-67 on dynamic image safety.

Prof. Raymond T.F. Cheung, Professor, and Chief Neurologist, Department of Medicine, Queen Mary Hospital, University of Hong Kong, Hong Kong SAR, MD, PhD, Neurology, WOnt.

Table 1

Experiment one: The presence of vection without OKN			Experiment two: The presence of OKN without vection		
rotating speed of the stimuli (dps)	retinal slip velocity (dps)	post-exposure SSQ nausea sub-scores: mean (SE)	rotating speed of the stimuli (dps)	retinal slip velocity (dps)	post-exposure SSQ nausea sub-scores: mean (SE)
0	0	29.3 (6.5)	0	0	14.3 (5.1)
2	2	32.0 (8.0)	30	2.1	35.4 (9.2)
14	14	58.6 (9.4)	60	12.2	42.2 (9.3)
34	34	60.0 (12.7)	90	48.6	34.1 (9.4)