Visually Induced Motion Sickness with Radial Displays: Effects of Gaze Angle and Fixation

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Background: Exposure to moving visual scenes can induce illusory feelings of self-motion (vection) and visually induced motion sickness in stationary observers. We have investigated the effect of viewing conditions on motion sickness in a radial optic flow environment, simulating the situation in which an observer shifts gaze in order to sample from the environment. In view of the spatiotemporal structure of radial flow patterns, vection magnitude and motion sickness were expected to increase when gaze position was directed away from the focus of expansion. ***Methods:*** There were 12 participants who were exposed to an expanding-contracting radial optic flow pattern under four viewing conditions: 1) fixation at the focus of expansion; 2) fixation at targets located 16° eccentric with respect to the focus of expansion; 3) consecutive gaze shifting between the focus of expansion and eccentric located targets; and 4) free viewing. Subjective measures of motion sickness and vection were obtained and gaze position was monitored using video-oculography. ***Results:*** Forced eccentric gaze position (conditions 2 and 3) significantly increased the level of motion sickness and facilitated vection. Mean accumulated sickness ratings in conditions 2 and 3 were about 20% higher than the conditions in which participants were free to move their eyes or were asked to fixate at the focus of expansion, and this trend was consistent across the different sickness measures employed. ***Conclusion:*** Optic flow appears to interact differently with different portions of the retina and, in central vision at least, visually induced motion sickness is influenced by retinal image velocity.

Keywords: radial optic flow, gaze position, vection, motion sickness.

IN BOTH REAL AND synthetic environments, movement within an observer's visual field may induce an illusory perception of contradirectional self-motion (vection) in stationary observers (9,19). Visually induced motion sickness is frequently reported while interacting with synthetic environments (4,16) and unexpected incongruence between the input provided by different sensory systems involved in the computation of self-motion (i.e., visual, vestibular, and somatosensory modalities) is often accepted to be the main cause (21,22).

Differences in viewing conditions are known to affect motion sickness during optokinetic drum stimulation (8,27). However, with this form of display a change in fixation position will not alter the visual stimulus. Furthermore, uniform texture flows, as are seen within optokinetic drums, seldom occur in either real or simulated environments. Other texture flows, such as expanding radial optic flow, which induces a perception of forward self-motion, might be expected to affect motion sickness differently from lateral movement. This is because the spatiotemporal structure of radial optic flow is not constant: the local image velocity at the focus of expansion (FOE) is zero and increases with eccentricity. This type of optic flow also produces a different stimulus when gaze position changes. With the FOE centered on the fovea(s), the situation is simulated in which gaze is in the direction of heading, but this is not the case when fixation is eccentric. The issue addressed here was whether there is a difference in nauseogenicity when fixation is at the FOE compared with when it is away from the FOE, simulating a situation in which the observer shifts gaze in order to sample from the environment.

Previously it has been shown that during exposure to radial optic flow patterns, susceptible participants tended to concentrate their visual attention around the FOE, showed a more limited variability in gaze behavior, and fixated for longer periods than non-susceptible participants (29). However, since sickness was not assessed per-exposure in this study, it was not clear whether the limited and inflexible pattern of visual search increased the level of sickness or whether the occurrence of sickness may have instigated participants to restrict their gaze around the FOE in an attempt to alleviate sickness (29).

Indirect support for the latter interpretation comes from a study by Webb and Griffin (31). Vection magnitude and motion sickness measures were obtained while participants tracked either a single moving dot or a full screen of laterally moving dots. Although participants reported more vection with full-field stimulation, motion sickness did not significantly differ between the two conditions. The apparent dissociation between vection and motion sickness led the authors to hypothesize that they were dominated by peripheral and foveal

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stimulation, respectively. There is strong evidence, however, that this functional foveal-peripheral dichotomy cannot be upheld. First, motion sickness has been reported with foveal vision masked (6), and second, central and peripheral stimulation yield comparable effects with regard to vection when they are equated for retinal area and specify a background surface (10,28). Nevertheless, it cannot be ruled out that central vision, rather than foveal vision, plays an important role in the generation of motion sickness. Increased velocity of the stimulus displayed has been shown to lead to an increase in the occurrence of motion sickness (13,24), and this may also explain why susceptible participants in Turner and Kendrick's study (29) limited their visual attention to around the FOE, as this would have limited retinal image velocity in central vision.

The only previous investigation of the effect of viewing conditions in a radial optic flow environment is that of Sparto et al. (25). In this study, participants performed gaze shifting tasks in order to locate targets superimposed on a radial optic flow background. The level of motion sickness was found to be lower than that reported during the use of flight simulators or head mounted displays, which led the authors to conclude that gaze shifting is tolerated well. However, short-exposure durations within each trial (90 s) and long inter-trial rest intervals (3 min), during which some recovery was likely to have taken place, may limit the validity of this interpretation to short-term exposures. Although their experiment was not designed to investigate the effect of viewing conditions as such, it is of interest to note that motion sickness during gaze shifting tended to be slightly higher than during central fixation.

To investigate whether viewing conditions affect visually induced motion sickness, we evaluated it in four situations: 1) gaze position fixed at the FOE; 2) gaze position fixed on a position eccentric with respect to the FOE; 3) consecutive gaze shifting between the FOE and eccentrically located target positions; and 4) spontaneous unrestricted gaze. In addition to subjective measures of motion sickness, we obtained vection data and eye movement recordings using video-oculography. On the basis of previous studies, forced eccentric gaze position (conditions 2 and 3) was hypothesized to exacerbate visually induced motion sickness in comparison with the other two conditions (conditions 1 and 4).

METHODS

Participants

There were 12 healthy Japanese male participants with a mean ± SD age of 22.58 ± 1.31 yr who gave their informed consent to participate in the study, following its approval by the Waseda University Ethical Advisory Committee. All participants had intact vestibular function and were not receiving any medication.

Apparatus and Stimuli

Participants were seated in a dark room. The head of each participant was stabilized by means of a head/chin rest. The stimuli were presented on a rear projection TV (ELS-57P, Epson, Nagano, Japan; screen size 126 × 71 cm, 1024 × 768 pixels) at a viewing distance of 48 cm. The visual field was 68.9° (horizontal) × 52.3° (vertical) of visual angle due to the physical restrictions imposed by the eye tracker. Stimuli were presented at a rate of 60 Hz by means of an Intel Extreme Graphics card (64 Mb), which was controlled by Matlab (version 6.5, MathWorks, Natick, MA) running the Cogent Graphics Toolbox. Acoustic localization cues were masked by pink noise (75 dB) transmitted to earphones worn by the participant.

Eye movements were measured continuously throughout exposure to the visual stimulus using an eye-tracking system which was composed of two CCD cameras attached to goggles (ET-60H, New Opt Co., Kanagawa, Japan). Eye movement recordings were processed using an image analysis system programmed using PC software (LabView Vision, National Instruments, Austin, TX), which enabled analysis of horizontal and vertical eye positions from the relative position of pupil center.

The visual stimulus consisted of an expanding-contracting random dot optic flow pattern simulating oscillating translational motion in the anterior-posterior axis at 0.2 Hz (average optical velocity $26° \cdot s^{-1}$), which has previously been shown to be a particularly provocative stimulus (6). The display consisted of 500 white dots each with a luminance of 124 $cd \cdot m^{-2}$ randomly positioned on a black background of 0.51 $cd \cdot m^{-2}$ (**Fig. 1**). Dot velocity and size varied exponentially as a function of their simulated location in depth. Dot size at the eye ranged from 0.12° at the middle to 4.53° at the periphery. Five fixation crosses were superimposed on the optic flow pattern: a center fixation cross and four eccentric fixation crosses 16° to the left, right, below, and above the center fixation cross. Behind each of the five fixation points, a black disk subtending 7.6° of visual angle was added in order to reduce reflexive eye movements as well as to keep foveal stimulation constant across different conditions.

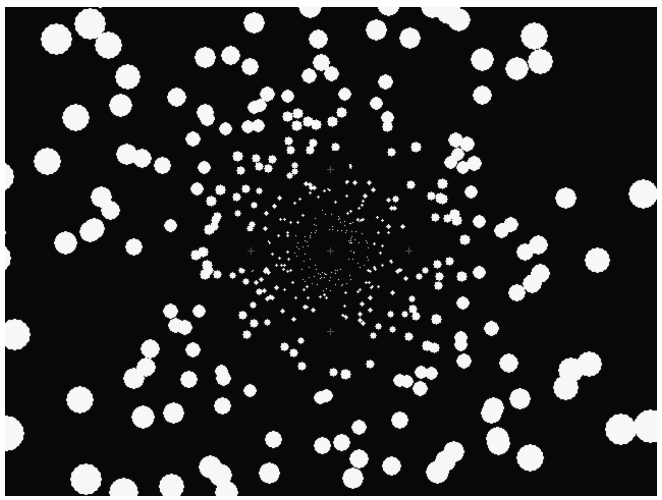

Fig. 1. Sample frame of the radially expanding-contracting optic flow pattern. The pattern oscillated at a frequency of 0.2 Hz.

Procedure

Four different viewing conditions were created:

1. Central fixation (CF)—during the trial participants were instructed to fixate on the central fixation cross.
2. Fixation eccentric (FE)—participants were instructed to keep fixating on one of the four eccentric fixation crosses throughout the experiment. The number of participants fixating each of the fixation crosses was balanced across conditions with three participants for each fixation cross.
3. Gaze shifting (GS)—participants were asked to move fixation from the central cross to each of the five fixation crosses in a fixed sequence. An auditory cue (750 Hz, 200-ms duration) was presented to serve as the go signal to perform a saccade to the eccentric fixation cross. After 7.5 s, another auditory cue (500 Hz, 200-ms duration) was presented to serve as the signal to return to the central cross. After a further 7.5 s, the next eccentric cross in the sequence was fixated, and so on. The sequence followed a counter clockwise direction, and 10 full circle repeats were performed (**Fig. 2**).
4. Free view (FV)—participants were allowed to look anywhere on the screen. They were also instructed not to stare through the screen.

The stimulus presentation was identical in all four conditions, and the auditory cues were also present in all four conditions.

Trials for each of the four conditions lasted for 10 min and were separated by at least 24 h to limit any habituation to the stimulus. To avoid possible circadian rhythm effects, each session took place at the same time of day. A repeated measures design was used with each participant acting as his/her own control. To minimize order effects, the order in which the four conditions were presented was balanced using a 4×4 Latin square design.

Prior to the first session, participants received written instructions and a demonstration. Vection was defined as a compelling feeling of self-motion, such as "the feeling you get when a train moves next to you and you mistake it for your own motion." To ensure participants differentiated between object- and self-motion, they were asked during this briefing to view a vertically translating optic flow pattern until a compelling sensation of vertical linear self-motion was reported. This typically occurred after about 15 s. When they indicated that they fully understood the task, the eye tracker was calibrated and the experiment commenced.

Measures

All questionnaires and written instructions were translated from English into Japanese by experienced bilingual experts. To ensure validity, questionnaires were translated back into English and subsequently crosschecked. Participants rated the severity of their motion sickness every minute on Bagshaw and Stott's (1) sickness scale (1 no symptoms; 2 mild symptoms, but no nausea; 3 mild nausea; 4 moderate nausea).

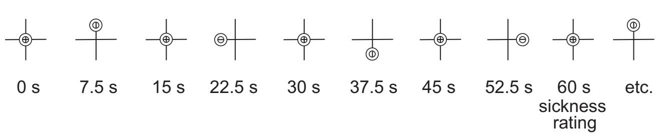

Fig. 2. Order of fixation position (circle) in the gaze-shifting condition.

To avoid participants making any head movements, they were asked to indicate the level of sickness with their left hand. The experiment was stopped at sickness rating 4 or after 10 min, whichever was the sooner. Participants who reached a sickness rating of 4 and stopped before 10 min were assigned continuation values of 4. All the participants were initially symptom free and the measures of interest were the time for participants to first report a sickness rating of 2 ('time to sickness rating 2') and 3 ('time to sickness rating 3'), the maximum sickness rating, and the sum of the sickness ratings over the 10-min exposure duration ('accumulated sickness rating'). If no symptoms were reported, accumulated sickness rating and symptom onset times of 11 were recorded.

At first sight, the use of an additional and widely used motion sickness measure such as the simulator sickness questionnaire (14) would have been beneficial. Questionnaires such as the simulator sickness questionnaire should be treated with caution, however, when used with a non-English population, and may be in need of cultural validation rather than mere translation (15). It was, therefore, decided to use the less equivocal Bagshaw and Stott's rating scale.

To evaluate the time course and total duration of vection, participants were instructed to press a button whenever they experienced vection, and to keep it depressed for as long as they experienced it. Vection onset latency was defined as the time it took for participants to first press the button. Vection duration was defined as the percentage of the total exposure time that vection was reported. Vection magnitude was assessed post-exposure by asking participants to rate their experience in terms of the following question: 'While watching the display, did you get the feeling of motion? Did you experience a compelling sensation of self-motion as though you were actually moving?' The endpoints of the 7-point Likert scale were anchored as 'not at all' (1) and 'very much so' (7).

The eye movements recorded in condition FV were analyzed using three different dependent variables. These were the variance in eye gaze coordinates along the horizontal and vertical meridians, and the average path length (the overall sum of displacement divided by the duration of exposure). To identify the areas of the visual stimulus to which participants were attending, recordings of the eye positions over the trial were overlaid by a grid with a resolution of $2 \times 2°$ of visual angle. Based on the total amount of time spent in each of the squares, contour maps were created representing the areas where participants' visual attention was focused and the amount of time spent there expressed as the percentage of the total exposure duration.

Analysis

Based on Turner and Kendrick's (29) observation that gaze behavior varies as a function of susceptibility, participants in condition FV were separated into susceptible and non-susceptible groups on the basis of their maximum sickness ratings. The eye movement data of one participant could not be used for technical reasons, and these were discarded in the analysis. Three participants comprised a higher susceptibility group (max sickness rating ≥ 3), whereas the remaining eight participants formed a lower susceptibility group (max sickness rating ≤ 2).

Statistical data analysis was performed using the software package SPSS (version 13). An initial analysis of the data revealed that no significant order effect was present. For all groups of non-parametric dependent variables (accumulated sickness ratings, vection magnitude ratings), data were compared using Wilcoxon signed ranks tests. For all groups of parametric dependent variables (symptom onset time, vection onset, vection duration) that passed the tests for normality, data were compared using Tukey's HSD tests. Correlations between different groups of measurements were assessed by Spearman's rho.

RESULTS

Table I shows the number of participants reaching each sickness rating before the 10-min maximum time cut-off. Because of the severity of motion sickness symptoms experienced, one participant requested termination of the trial before the maximum 10-min time cut-off in conditions GS, FV, and CF. One participant requested termination of the trial before the maximum 10-min time cut-off in condition FE and a further participant stopped during condition GS.

The time course of mean sickness ratings is shown for each of the four conditions in **Fig. 3A**. Conditions FV and CF produced the lowest mean sickness ratings while conditions FE and GS, in which peripheral fixation was forced, resulted in the highest ratings. Although data were not collected beyond 10 min in this study, two participants reported feeling slightly nauseous for more than 2 h after being exposed to both condition GS and FE. The mean accumulated sickness rating was significantly higher in condition GS (19.83) than in condition CF (16.17) and condition FV (15.83) ($p < 0.05$, Wilcoxon). The mean accumulated sickness rating was higher in condition FE (18.50) than in condition FV ($p < 0.05$, Wilcoxon) and CF, although the latter difference failed to reach the level of significance required ($p = 0.079$).

TABLE I. NUMBER OF PARTICIPANTS REACHING EACH SICKNESS RATING BEFORE MAXIMUM 10-MIN CUT-OFF.

	Condition			
Sickness Rating	CF	FE	GS	FV
2	8/12	9/12	9/12	9/12
3	3/12	5/12	4/12	3/12
4	1/12	1/12	2/12	1/12

CF=central fixation; FE = fixation eccentric; GS = gaze shifting; FV = free view.

Fig. 3B and C show the times to sickness rating 2 and 3, respectively. Symptom onset times tended to be shorter during forced eccentric fixation (FE and GS). Wilcoxon signed ranks tests demonstrated that time to sickness rating 2 was significantly shorter in condition GS than in condition CF ($p < 0.05$). Time to sickness rating 3 was significantly shorter in condition FE than in condition FV ($p < 0.05$).

Of the 12 participants, 11 experienced linear vection in the direction opposite that of the display motion in all of the four conditions. One participant reported vection and mild symptoms in condition GS only. This may have been a primacy effect as the participant was exposed to condition GS first.

Vection magnitude ratings were higher in conditions FE (5.00) and GS (5.17) than in conditions CF (4.58) and FV (4.17). Although none of the differences were statistically significant, in retrospective questioning 10 of 12 participants reported vection magnitude to increase with gaze eccentricity (i.e., conditions FE and GS). Vection duration also tended to be slightly higher in conditions FE (55.5%) and GS (57.1%) compared with conditions CF (52.6%) and FV (54.5%), although these differences failed to reach the required significance level. Mean vection onset time was shortest in condition GS (43.1 s), followed by condition FE (101.9 s), FV (113.6 s), and CF (115.5 s). The means were heavily influenced by the fact that on trials in which no vection was reported, onset times were assigned values equal to the trial duration, 600 s. When these trials are excluded, the means become 43.1 s (GS), 56.7 s (FE), 69.4 s (FV), and 71.7 s (CF). Gaze eccentricity thus slightly reduced vection onset times (i.e., GS, FE < CF, FV), although these differences were not significant. **Table II** shows the correlations (Spearman's rho) between the maximum sickness ratings and vection magnitude, duration, and onset times for each of the four conditions and pooled over the four conditions. All three vection measures were strongly correlated with maximum sickness ratings.

On- and off-line inspection of the eye movement data for conditions CF, FE, and GS indicated that all participants complied with the experimental protocol, i.e., in each of the three conditions deviation from the target position (i.e., fixation cross) was within $\pm 4°$ of visual angle. In the first part of the analysis of the eye movement recordings in condition FV, each measure was correlated with the accumulated sickness rating. Although non-significant, a consistent trend was found in that accumulated sickness ratings were negatively correlated with horizontal axis variance [$r_s(11) = -0.336$, $p = 0.313$], vertical axis variance [$r_s(11) = -0.221$, $p = 0.514$], and average path length [$r_s(11) = -0.378$, $p = 0.252$].

Fig. 4 shows contour maps of average gaze position in condition FV for the non-susceptible and susceptible group. For both groups, gaze position was limited to an area with a radius of approximately 6° around the FOE (center display) during 75% of the total exposure duration, of which 50% was concentrated in an even smaller

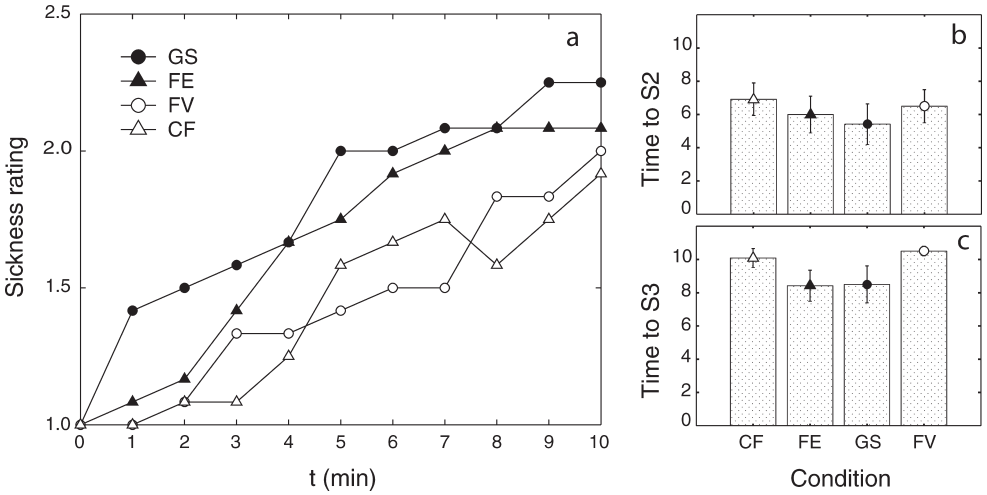

Fig. 3. A) Mean sickness rating as a function of time for each of the four conditions. Filled symbols represent the two conditions where fixation was away from the FOE. B) Mean (± SEM) time to sickness rating 2 (S2). C) Mean (± SEM) time to sickness rating 3 (S3).

area, indicated by the dark area. The difference between the groups becomes more apparent when gaze stability is analyzed over the time period of the trial. Fig. 4C and D show the mean standard deviations of horizontal (x) and vertical (y) eye position (degrees), respectively, over time (1-min time window) for the susceptible and non-susceptible group. Unlike the non-susceptible group, participants in the susceptible group showed a lower variability in gaze position at the onset of the trial, but tended to increase variability in both horizontal and vertical scanning as the trial progressed.

To further examine the relationship between the variability in gaze position and motion sickness, the ratios of the summed standard deviations between minutes 1–4 and minutes 6–9 were calculated for both horizontal and vertical directions, and were subsequently correlated with the accumulated sickness ratings for all 11 participants for whom eye movement data was available. Positive correlations between the accumulated sickness rating in condition FV and the ratios for the horizontal [r_s (11) = 0.423, p = 0.195] and vertical directions [r_s (11) = 0.621, p = 0.042] indicate that those participants who reported more motion sickness tended to increase their variability in gaze position over time.

TABLE II. SPEARMAN CORRELATION COEFFICIENTS FOR MAXIMUM SICKNESS RATING AND VECTION MAGNITUDE, DURATION, AND ONSET FOR EACH CONDITION INDIVIDUALLY AND POOLED.

Condition	Vection Magnitude	Vection Duration	Vection Onset
GS	r_s = 0.422	r_s = 0.598*	r_s = −0.587*
FE	r_s = 0.627*	r_s = 0.628*	r_s = −0.321
FV	r_s = 0.773*	r_s = 0.528	r_s = −0.611*
CF	r_s = 0.530	r_s = 0.515	r_s = −0.563
Pooled	r_s = 0.599*	r_s = 0.661*	r_s = −0.905**

*, ** Correlation is significant at the 0.05 and 0.01 level, respectively (2-tailed). GS = gaze shifting; FE = fixation eccentric; FV = free viewing; CF = central fixation.

DISCUSSION

The aim of this study was to investigate the effect of gaze position on visually induced motion sickness in radial optic flow environments, and it was hypothesized that eccentric gaze position with respect to the FOE would exacerbate visually induced motion sickness. Despite relatively short exposure durations (10 min), this clearly occurred. Forced eccentric gaze position (FE and GS) slightly decreased vection onset times, increased vection magnitude ratings and duration, and significantly exacerbated the level of motion sickness in comparison with conditions in which participants were free to move their eyes or were asked to fixate on the center fixation cross (FV and CF, respectively).

The finding that motion sickness during GS did not differ from the level reported during FE indicates no surplus effect of the eye movements, unless it was balanced by an ameliorating effect of the recurrent return to the central area of the display. The finding further indicates that the elevated level of sickness in condition FE does not pertain to maintained eccentric gaze position as such. Also, no difference was found between the CF condition and the FV condition. However, this is hardly surprising because the eye movement records showed that in the FV condition, gaze position was largely limited around the FOE.

The present results suggest that the position and direction of the optic flow structure interacts with the exposed retinal area in the generation of visually induced motion sickness. Local image velocity increases toward the periphery in radial displays, and because of this, one possible explanation for the observed effect is the increase in retinal image velocity in central vision during fixation away from the FOE. Apart from the dominant role it plays in, for example, the control of optokinetic nystagmus (12), retinal image velocity in central vision may also prove to be the most significant signal driving visually induced motion sickness. However, if velocity is unimportant then the results are also consistent with potency increasing away from the fovea. This is because the visual stimulus is of fixed size,

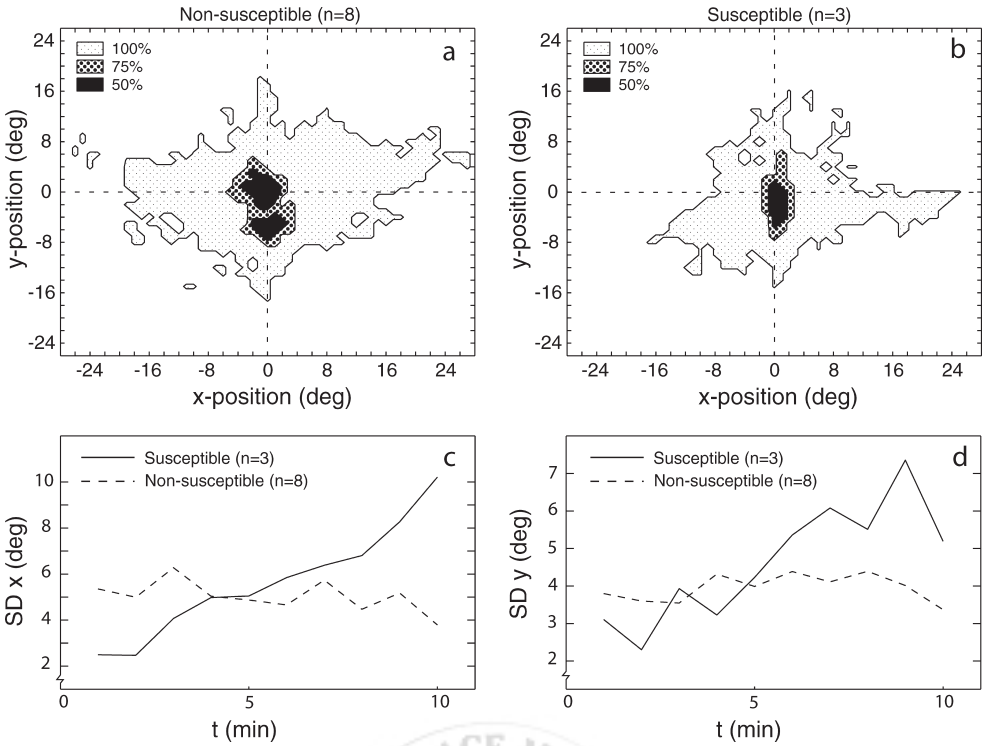

Fig. 4. Mean variation in eye position in the FV condition over the whole trial. Top row: contour map of average gaze position for the A) non-susceptible and B) susceptible group. Areas indicate the percentage of the exposure duration that gaze position was in the corresponding area. Bottom row: time course of SDs of C) horizontal and D) vertical eye position in degrees as a function of susceptibility.

and as fixation at the FOE and eccentric fixations allow different portions of the retina to be stimulated, such inhomogeneity of the retina would produce the results seen.

A further factor that may be relevant is that heading judgments are less accurate in peripheral than in central vision with radial flow fields. Disparities between gaze and heading direction as small as 10° have been shown under some circumstances to reduce performance to near chance level (30). In the current study, it is reasonable to assume that heading accuracy and precision during eccentric viewing conditions was also impaired. While the relationship between heading performance and motion sickness is not evident, disparities between gaze and heading direction could have compromised information of near future motions, thereby possibly deteriorating the ability to anticipate incoming sensory cues, which, in turn, has been shown to be associated with increased motion sickness (18,23,26).

A possible confounding factor in the current study is the fact that eccentric fixation not only resulted in an increase in motion sickness, but also in vection. Within studies similar to ours, the occurrence of vection has often been assumed, but rarely assessed, which only adds to the controversy about the role of vection in visually induced motion sickness. Although not all of the differences in vection measures reached the required significance level, the consistent trend observed across these measures is an important indicator of association between vection and visually induced motion sickness.

The strong correlations between vection and motion sickness indicate that the participants who reported higher levels of motion sickness were those who also reported more vection. However, it is unclear whether motion sickness is caused by vection or the sensory conflict that often, but not necessarily, accompanies vection. For example, compelling sensations of vection are reported during exposure to a constant velocity radial optic flow pattern without concomitant motion sickness (7). This vection should be no different from that experienced during true motion at constant velocity, and it follows that vection does not necessarily reflect sensory conflict. Alternatively, the finding that motion sickness is absent by some participants who still experienced vection may indicate that some individuals are insensitive to sustained conflict. Thus, whereas vection is often accompanied by the occurrence of motion sickness, the two may be independent.

Two factors may have facilitated the occurrence of vection during the peripheral fixation condition in the current study. First, since vection has been shown to increase with image velocity (2,5,17), the increased vection during peripheral fixation may be explained by the increased retinal image velocity in the central vision. Second, relative motion of visible parts of a subject's body or external objects relative to the scene are also known to facilitate vection (3,11,20). In the present study, the visible parts of the orbital rims and the eye tracker increased with gaze eccentricity, which may have accounted for the observed differences.

The negative correlations between motion sickness and the different eye movement measures (i.e., horizontal and vertical axis variance, average path length) would appear to be consistent with previous findings by Turner and Kendrick (29) and suggest that suscep-

tible individuals show less variability in gaze behavior than non-susceptible individuals. However, an unexpected finding was that susceptible participants tended to increase gaze variability over time, so this consistency was only true during the early stages of the trials, and the opposite was seen in the later stages. If it is, indeed, the case that eye movements per se do not increase symptoms, then one would expect those participants to experience greater symptoms toward the end of the trial because of the greater time they spent fixating in the periphery of the stimulus. This was seen to happen.

In summary, we have shown that gaze eccentricity with respect to the FOE increases vection and visually induced motion sickness. Because of the interaction between the optic flow structure and the exposed retinal area, we suggest that visually induced motion sickness is affected by retinal image velocity in central vision, and that gaze position does affect visually induced motion sickness.

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