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Visually induced motion sickness: Single- versus dual-axis motion

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ABSTRACT

The majority of studies into visually induced motion sickness (VIMS) either use complex motion scenarios or are limited to single-axis motion. This study compared VIMS during single- and dual-axis motion. Twelve participants were exposed to (i) oscillating roll motion, (ii) linear motion in the fore-and-aft axis, and (iii) spiral motion, i.e. the summed direction of both of these flow vectors. Increased sensory conflict during exposure to spiral motion was hypothesised to increase the level of VIMS compared with exposure to its constituent motion patterns in isolation. Unexpectedly, spiral motion was not found to be more provocative than either of the two single-axis motion patterns, and this finding appears to be inconsistent with VIMS being determined by simple summation of the provocative stimuli. In the spiral motion condition, an atypical decrease in VIMS was observed during exposure, which was consistently preceded by a reduction in reported vection. It was hypothesised that the abstract nature as well as the unusual motion profile in the spiral motion condition may have rendered the stimulus increasingly 'improbable' and ultimately being disregarded, or 'quarantined', as an orientation cue by the central nervous system. The results are discussed in the context of methodological consequences for VIMS research and potential limitations of the use of abstract stimuli.

1. Introduction

To date, the relationship between optic flow characteristics and visually induced motion sickness (VIMS) has been mainly investigated using optokinetic drum stimulation. However, uniform texture flows, as are seen within optokinetic drums, seldom occur in either real or simulated environments where motion in the fore-and-aft axis is dominant. Furthermore, these studies are typically limited to single-axis motion whereas many real world scenarios are characterised by displays of optic flow simulating complex patterns of self-motion. Hence, the question addressed in this paper is how VIMS varies as a function of multi-axis motion.

The severity of motion sickness is generally assumed to be monotonically related to the degree of conflict in one or more sensory channels [1,2]. Findings such as the tendency of visual-field rotation around earth-horizontal axes (i.e. pitch and roll) to be more provocative than rotation around the earth-vertical axis (i.e. yaw) [3–5] are usually explained by differences in the degree of sensory conflict, or better, neural mismatch. The absence of an expected signal from the semicircular canals results in sensory conflict during visual-field rotation in all three rotational axes, but during rotation of the visual stimulus around earth-horizontal axes (unlike earth-vertical axes) there is additional conflict due to the expected, but absent, signal from the otoliths.

Support for a monotonic-additive effect of the degree of conflict on VIMS comes from optokinetic drum studies in which the orientation of the stripes is systematically altered. In a study by Andre et al. [6], observers were exposed to 60°/s optokinetic drum stimulation with the inner wall of the optokinetic drum covered by either vertical stripes or off-vertical stripes tilted 15° in the direction of drum movement. Under the tilted drum condition, in which the stripes moved down and to the right, participants reported complex vection with both a horizontal and vertical component. As predicted, the added mismatch between the visual vertical and the vestibular vertical in the tilted condition significantly increased gastric tachyarrhythmic activity, although no significant differences were found in subjective measures of VIMS. More recently, Bubka and Bonato [7] conducted a similar experiment in which observers were exposed to 60°/s optokinetic drum stimulation with the drum either aligned to the earth-vertical axis (yaw), or tilted relative to the axis of rotation (5° and 10° tilt). In this study, drum tilt did result in a significant increase in VIMS.

Although these studies provide some support for the notion that VIMS and the degree of conflict show a monotonic relationship, these studies are limited to visual-field rotation. In a previous study we have shown that the frequency-dependence of VIMS may differ between rotational and translational visual-field motion [8] and it cannot be automatically assumed that findings based on rotational visual-field motion can be extrapolated to different motion scenarios, including translational visual-field motion.

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Hence, in this study, the hypothesis of a monotonic additive effect on VIMS of combined translational and rotational visual-field motion was tested.

Stationary observers were exposed to optic flow patterns simulating oscillating roll motion, oscillating fore-and-aft motion, and the summed direction of both flow vectors, i.e. spiral motion. During oscillating fore-and-aft motion, conflict is caused by the absence of corresponding signals from the otolith organs, whereas oscillating roll motion results in both semicircular-visual and otolith-visual conflict, as described above. Predicated on an additive model, dual-axis motion was hypothesised to result in higher levels of VIMS compared with single-axis motion because of the greater total conflict.

An additional aim of this study was to investigate the relationship between VIMS and vection. Although VIMS is often referred to as "vection induced motion sickness" [7,9], contradictory results are found in the literature as to the role of vection in the generation of the symptoms. Whereas some authors suggest vection to be a necessary condition for VIMS to occur [10], others have failed to find a relationship between vection and VIMS [11]. To gain a better understanding of the relationship between vection and VIMS, apart from its occurrence, the time course of vection was investigated in relation to the development of VIMS.

2. Methods

2.1. Participants

Twelve healthy participants (5 female, 7 male) with a mean (±SD) age of 26.08 (±6.13) years gave their informed consent to participate in the study, following its approval by the Loughborough University Ethical Advisory Committee. All had intact vestibular function, none were receiving any medication, and all had normal or corrected-to-normal vision.

2.2. Trial

Trials took place in a dark room, and each participant had their head stabilised by means of a head/chin rest (Fig. 1). The visual stimulus was produced using Matlab (version 6.5; Cogent Graphics Toolbox) controlling a Matrox Millennium P750 graphics card (64 Mb) running on a DELL GX computer. The images were back-projected onto a screen (190 cm × 145 cm) with a Hitachi CP-X958 W/E projector (1024 × 768 pixels). To occlude the edges of the screen and other peripheral features, participants wore goggles, which limited the visual field to 65° (h) × 59° (v) of angle at a viewing distance of 80 cm. Acoustic localisation cues were masked by pink noise (75 dB) transmitted to earphones worn by the participant. In addition, auditory alerting bleeps of different frequencies (500, 750, and 1000 Hz at 100 dB) were played at random intervals throughout the exposure duration. Communication with the participants during exposure was via a microphone. To monitor participant's well being and to ensure compliance with instructions, an infrared camera was placed on the side pointing towards the participant's face and relaying images to a monitor outside the viewing booth.

2.3. Stimulus

The visual stimulus consisted of 500 moving white filled-in circles (10.82 cd/m2) on a black background (0.35 cd/m2). All stimuli were presented at a refresh rate of 60 Hz. For technical reasons, there were no dots at the very centre of the visual scene, and as a consequence, there was a black disc subtending 8.75° of visual angle (Fig. 1). A red (fixation) dot (0.57° of visual angle) was projected at eye height in the centre of the screen.

Three optic flow patterns were used.

Condition R: oscillating roll motion was simulated by sinusoidal rotation of the random dot pattern around the fore-and-aft axis at a frequency of 0.2 Hz (peak-to-peak amplitude of 120°, average angular velocity of 48°/s).

Condition FB: radially expanding/contracting displays simulated sinusoidally oscillating forward and backward linear motion along the fore-and-aft axis through a 3D cloud of randomly positioned dots. 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. The stimulus oscillated at a frequency of 0.2 Hz with a peak angular velocity of 34°/s which pertains to a perceived peak velocity of 0.97 m/s.

Rotational and translational motion patterns of equal nauseogenicity were identified in a pilot study, hence no difference in symptom severity was expected between the two single-axis motion patterns.

Condition RFB: summation of the flow vectors in condition R and FB simulated spiral motion, i.e. simultaneous in-phase roll and fore-and-aft motion.

2.4. Procedure

Participants were exposed to each of the three conditions for 20 min, and trials were separated by at least 24 h to limit any habituation to the stimulus. To avoid possible circadian rhythm effects, each trial took place at the same time of day. A repeated measures design was used, and to minimise order effects the sequence in which the three conditions were presented was balanced using a Latin square design. Prior to the first session, participants received written and verbal instructions. The phenomenon of vection was explained to them while they were watching an upward translating random checker optic flow pattern. To ensure they differentiated between object- and self-motion, they watched the

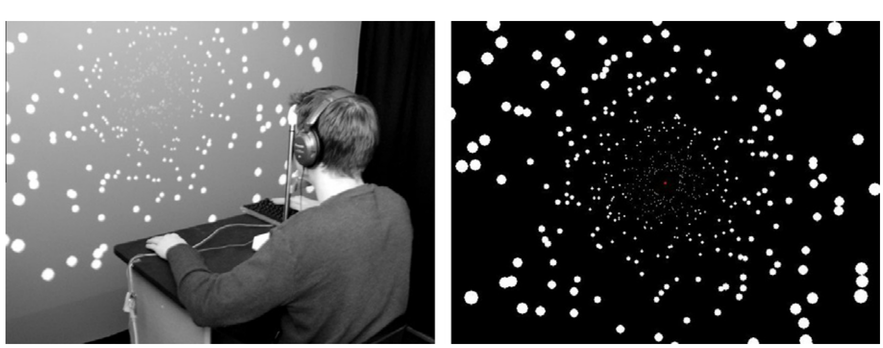

Fig. 1. Experimental setup (left), and sample frame of the optic flow pattern (right).

pattern until they reported a compelling sensation of vertical linear self-motion. This typically occurred after about 15 s. When they indicated that they fully understood the task, the experiment commenced. They were instructed to focus on the central fixation dot for the duration of the experiment and indicate whenever they experienced vection.

2.5. Metrics

Motion sickness symptoms were assessed using the Simulator Sickness Questionnaire (SSQ) [12]. Measures of interest were the change (post–pre exposure score) in the SSQ total scores and the change in SSQ subscores (N, O, D) usually evaluated [12].

In addition to the SSQ, participants rated the severity of their motion sickness every minute on Bagshaw and Stott's [13] sickness scale (1 no symptoms; 2 mild symptoms, but no nausea; 3 mild nausea; 4 moderate nausea). The experiment was stopped at malaise rating 4 or after 20 min, whichever was the sooner. Participants who reached a malaise rating of 4, and stopped, before 20 min were assigned continuation values of 4. All the participants were initially symptom-free and the measures of interest were (i) the time for participants to first report a sickness rating of 2 (S2), (ii) the time to first report a rating of 3 (S3), (iii) the maximum sickness rating, (iv) the sum of the sickness ratings over the 20 min exposure duration ('accumulated sickness rating'). If no symptoms were reported, an accumulated sickness rating and symptom onset time of 21 were recorded.

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. The overall vection magnitude was assessed post exposure by asking participants to rate their experience in terms of the following question: 'Whilst watching the moving images, 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 rating scale were anchored as 'not at all' (1) and 'very much so' (7). Data analysis was performed using the software package SPSS (version 13). An initial analysis of the data revealed no significant order effect. For parametric and non-parametric dependent variables, data were compared using Tukey's HSD tests and Wilcoxon Signed Ranks tests, respectively. Two-tailed tests were employed when comparing conditions R and FB whereas comparisons involving condition RFB employed one-tailed tests. Correlations between different groups of measurements were assessed by Spearman's rho. Significance level was set to 0.05 for all tests.

3. Results

3.1. Sickness ratings

Table 1 shows the number of participants reaching each sickness rating before the 20 min maximum time cut-off.

The time course of mean sickness ratings, and the proportion of participants reporting vection, are both shown in Fig. 2. Note that the step change in proportion participants reporting vection is not constant and increases over time due to participant dropping out because of severe symptoms experienced. With regard to VIMS, it can be seen that in conditions R and FB the mean symptom ratings steadily increased over time, although some individual participants showed temporary decreases. In condition RFB on the other hand, a large drop in mean sickness rating was observed after around 500 s. This decrease in reported sickness was consistent across all participants with only two participants reporting a resurgence of symptoms after 840 s of which one reported a sickness rating of 4 ("drop out") at 1020 s.

Table 1
Number of participants reaching each sickness rating before maximum 20-min cut-off.

Sickness rating	Condition		
	R	FB	RFB
2	9/12	8/12	8/12
3	5/12	5/12	5/12
4	3/12	4/12	3/12

The accumulated sickness rating in condition RFB was slightly lower (mean = 34.5; SD = 18.2) than in conditions R (mean = 36.4; SD = 20.5) and FB (mean = 40.2; SD = 20.9). None of the differences were found to be statistically significant however (Wilcoxon Signed Ranks tests; $p > .05$).

To investigate whether the failure to find an effect of the experimental manipulation can be explained by the adaptation that appeared to have occurred in condition RFB (Fig. 2), only the first 420 s of the accumulated sickness ratings were analysed. Within this time period, the accumulated sickness rating in condition RFB (mean = 11.4; SD = 3.4) was found to be only slightly higher than in conditions R (mean = 10.7; SD = 4.2) and FB (mean = 11.1; SD = 3.6). Again, none of the differences were significant (Wilcoxon Signed Ranks tests; $p > .05$).

With regard to sickness rating onset times, the differences between the three conditions were also found to be small. Time to sickness rating 2 in condition R (mean = 12.1 min; SD = 7.5) was higher than that observed in condition FB (mean = 10.9 min; SD = 7.9) and RFB (mean = 9.9 min; SD = 8.2). Similarly, time to sickness rating 3 in condition R (mean = 15.9 min; SD = 7.3) was higher than that observed in condition FB (mean = 15.2 min; SD = 7.7) and RFB (mean = 14.7 min; SD = 7.7). None of the differences in either time to sickness rating 2 or 3 were found to be statistically significant (Tukey's HSD tests; $p > .05$).

3.2. Simulator Sickness Questionnaire

The SSQ total scores were found to be slightly lower in condition FB (mean = 31.2; SD = 26.1) in comparison to condition R (mean = 33.7; SD = 37.1) and RFB (mean = 33.3; SD = 35.1). Differences again were small and failed to reach the level of significance required (Wilcoxon Signed Ranks tests; $p > .05$). The SSQ subscores N, O, and D were also found to show only small differences between conditions, none of which were statistically significant.

3.3. Vection

With the exception of one participant in condition FB, vection was reported by all participants in all three conditions. In condition RFB, participants perceived both translational and rotational vection simultaneously and anecdotal reports from participants, following exposure, included descriptions of a corkscrew-like feeling of self-motion.

The overall magnitude was rated highest in condition R (mean = 5.9; SD = 1.3), followed by conditions FB (mean = 5.0; SD = 2.0) and RFB (mean = 4.8; SD = 1.4). The overall vection magnitude in condition R was found to be significantly higher than in condition RFB (Wilcoxon Signed Ranks tests; $p = 0.28$). None of the other differences were significant.

The mean percentage of the total exposure duration that vection was reported was also higher in condition R (mean = 67.3%; SD = 20.4) than in condition FB (mean = 66.1%; SD = 32.6) and RFB (mean = 56.2%; SD = 20.9). However, the differences were small and did not reach the level of significance required (Tukey's HSD tests; $p > .05$).

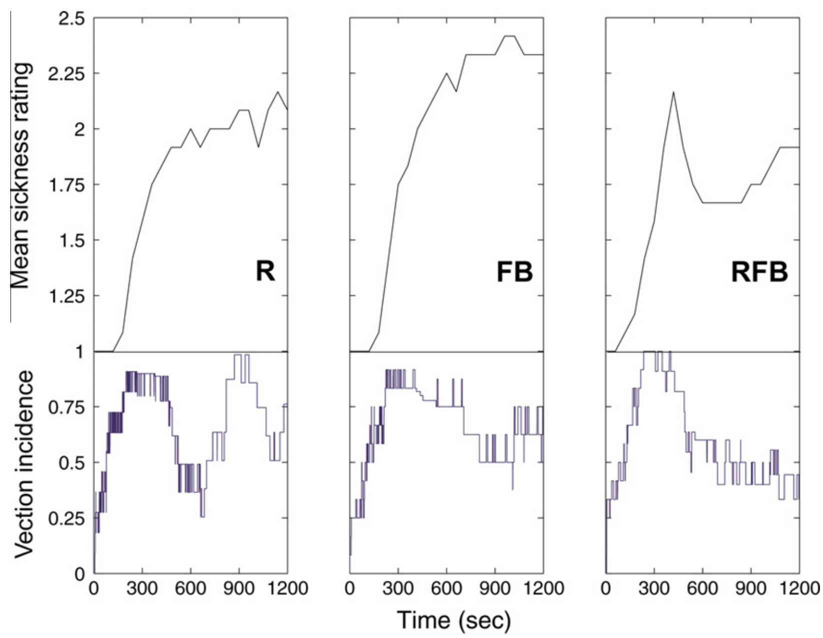

Fig. 2. Mean sickness ratings (top) and proportion of participants reporting vection (bottom) as a function of time for each of the three conditions (roll (R), forward–backward (FB), roll + forward–backward (RFB)).

Table 2
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 (s)
R	.539	.206	−.011
FB	.403	−.029	.124
RFB	.591*	−.025	.188
Pooled	.702*	−.179	.164

* Significant at the 5% level.

Mean vection onset time was highest in condition FB (mean = 183.8 s; SD = 328.8), followed by condition R (mean = 116.4 s; SD = 193.4) and RFB (mean = 94.0 s; SD = 84.4). Since vection onset times were not normally distributed, non parametric statistics were used which indicated no statistically significant differences between conditions (Wilcoxon Signed Ranks tests; $p > .05$).

Table 2 shows the correlations (Spearman's rho) between the maximum sickness ratings and the vection magnitude, the duration, and the onset times for each of the three conditions individually and pooled over conditions. The largest correlation coefficients were observed between maximum sickness ratings and vection magnitude.

4. Discussion

The purpose of this study was to investigate the issue of the addition of stimuli each of which produces VIMS. On the basis of classical sensory conflict theories [1,2], exposure to dual-axis motion (i.e. combined rotational and translational visual field motion) would be expected to increase the level of VIMS compared with exposure to its constituent parts in isolation considering the additional sensory conflict. Surprisingly this did not occur, and the results are difficult to explain in terms of a monotonic-additive model in which motion sickness is considered to be proportional to the degree of conflict [1,2].

Whereas the classical theories fail to explain the current results, the subjective vertical (SV) mismatch theory [14] would predict the differences in sickness between the three conditions to be much smaller with dual-axis motion not necessarily leading to higher sickness levels. This is because the SV mismatch theory assumes that all types of motion sickness have only one underlying conflict in common, namely, the conflict between the sensed and the subjective vertical, or internal representation of gravity. When considering the three conditions in terms of their effect on the subjective vertical, in condition R, the participant misses the mostly laterally oriented otolith stimulus corresponding to the lateral tilt with respect to gravity in the frontal plane. In condition FB the system misses the forward–backward otolith stimulus, which is perpendicular to the missing otolith stimulus of the stimulus in condition R. In phase addition of these stimuli has the effect that the two linear vectors sum up to a more diagonally oriented missing otolith stimulus. The absence of elevated sickness levels in the dual-axis motion condition RFB may be explained by the fact that the direction and amplitude of the subjective vertical did not sufficiently differ.

However, even though the SV mismatch theory may be able to provide an explanation for the finding that additional conflict as defined by the classical sensory conflict theories may not necessarily lead to increased sickness levels, it does not explain the mean decrease in sickness rating observed during condition RFB. When considering the time course of reported sickness, initially, sickness ratings in all conditions gradually increased over time by similar amounts. However, in the dual-axis condition RFB, an atypical decrease in mean sickness ratings was then observed. Although it is well known that habituation occurs after repeated exposure to a provocative visual stimulus [10,15–17], and that during trials individuals will, on occasion, report decreases in symptom magnitude as well as increases, this mean decrease during exposure appears to be a novel finding. The consistency across participants argues against this decline being an artefact.

Inspection of the time course of vection in condition RFB would suggest that on average the decrease in reported sickness was caused by the preceding reduction in reported vection. However, a similar decrease in vection was observed in condition R, but without a concomitant decrease in mean sickness rating. Unlike condition RFB, however, this loss of vection was only temporary and vection resurged in the second half of the session (see Fig. 2) and may explain the difference in reported sickness.

The individual records appear to be in line with this interpretation and showed that (i) the onset of symptoms was always preceded by the occurrence of vection, but may have lingered on after vection had dissipated and (ii) participants who did not experience motion sickness may nevertheless have experienced compelling sensations of vection. These findings provide further support for the contention that vection appears to be a necessary precursor of VIMS [10], whereas individual differences in sensitivity to sensory conflict may determine whether or not motion sickness occurs.

The observed reduction in vection across conditions was not uniform but differed qualitatively. Adaptation of vection as such is not a new finding, and has previously been shown to occur during prolonged stimulation for both linear [18] and circular vection [19]. The results of the present study, however, suggest that the rate of adaptation may not be homogeneous across axes and tended to be lower during fore-and-aft motion. From an ecological perspective this may perhaps not be too surprising when considering the dominance and relevance of fore-and-aft motion in the natural world.

Returning to the unusual decrease in reported VIMS in the dual-axis condition, this finding is even more striking when compared to results from a recent study by de Vries et al. [20]. In their study, the motion profile of the visual stimulus employed was similar to ours. Participants viewed a tour through a virtual environment in the fore-and-aft axis for a total duration of 50 min. In addition, roll motion (maximum amplitude of 16°) was superposed on this translation to increase the provocative nature of the stimulus. Despite the similarity in stimulus employed (i.e. linear fore-and-aft motion plus roll motion), and furthermore, the fact that individuals were exposed to the stimulus for more that than double the duration (20 vs. 50 min), sickness scores in the study by de Vries et al. showed the typical gradual increase over time.

So why is it that in response to the dual-axis motion pattern employed in our study participants no longer experienced vection after some time, and consequently reported a reduction in sickness? A clue to this question may lie in the characteristics of the visual stimulus. First, the motion profile is rarely encountered in real life. Optic flow depicting oscillating fore-and-aft motion may be experienced whilst being on a swing, but beyond childhood, relatively few people would have experience with this kind of stimulus. When combined with oscillating roll motion, the cork-screw like motion becomes arguably even more unnatural. Despite the similarity in the motion profile, no such reduction in sickness was however observed in the study by de Vries et al. [20]. Besides the smaller peak-to-peak amplitude of roll motion, an additional difference between the visual stimulus used by de Vries et al. and ours is that the random dot pattern lacked any pictorial realism and visual frame or polarity cues [21]. Taken together, over time, these factors may have rendered our stimulus increasingly less ‘plausible’, ultimately resulting in the visual stimulus being disregarded by the brain as an orientation cue. Recently, this concept has been put forward by Gresty et al. [22] and has been referred to as ‘quarantining’. Quarantining of the visual stimulus provides an explanation for the observed vection ‘drop-out’ indicating the transition from self-motion to object-motion perception. As a corollary, this in turn would have led to increased congruence between visual and vestibular self-motion cues and associated reduction in sickness.

5. Conclusion

Contrary to the expectation based on classical motion sickness theory (and consistent with the subjective vertical theory [14]), dual-axis motion did not increase the level of motion sickness compared with single-axis motion. Although at first sight this finding appears to be inconsistent with VIMS being determined by simple summation of the provocative stimuli, we cannot discount the idea that the observed results are because of ‘quarantining’ of the visual stimulus. Abstract stimuli simulating highly unusual motion profiles may be considered ‘improbable’ by the central nervous system and ultimately disregarded, or quarantined. From a methodological point of view, this finding illustrates the significance of assessing i) sickness not only pre- and post-exposure, but also during exposure, and ii) the development of vection over time. This enables the identification and interpretation of atypical time courses of sickness as the level of VIMS reported may not be entirely ascribed to the motion profile as defined by the optic flow pattern. This may be of particular relevance when employing highly abstract visual stimuli.

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