

Visually Induced Motion Sickness during Single and 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 anterior-posterior 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 motion sickness compared with exposure to its constituent motion patterns in isolation. Unexpectedly, spiral motion was not found to be more nauseogenic than either of the two single-axis motion patterns and this was consistent across participants. This finding argues against the magnitude of VIMS being determined by simple summation of the provocative stimuli.

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 translational motion 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 (Oman, 1982, 1991; Reason, 1978). 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) (Lo & So, 2001; Ujike et al., 2004; Yang & Pei, 1991) are usually explained by differences in the degree of sensory conflict. 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.

Further 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. (1996), 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 (2003) 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, it should be noted that these studies are limited to rotational motion. In a previous study we have shown that the frequency dependence of VIMS may differ between rotational and translational motion (Diels & Howarth, 2006) and it cannot be automatically assumed that findings based on rotational motion can be extrapolated to different motion scenarios, including translational motion. Hence, in this study, the hypothesis of a monotonic additive effect on VIMS of combined translational and rotational motion was tested.

Stationary observers were exposed to optic flow patterns simulating oscillating roll motion, oscillating linear motion in the anteroposterior axis, and the summed direction of both flow vectors, i.e. spiral motion. During oscillating linear 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. 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.

Methods

Twelve healthy participants (5 female, 7 male) with a mean (\pm SD) age of 26.08 (\pm 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.

Trials took place in a dark room, and each participant had their head stabilised by means of a head/chin rest. The visual stimulus was produced using Matlab (version 6.5; Cogent Graphics Toolbox) controlling a Matrox Millennium P750 graphics card (64Mb) running on a DELL GX computer. The images were backprojected onto a tangent screen (190 cm x 145 cm) with a Hitachi CP-X958W/E projector (1024 x 768 pixels). To occlude the edges of the screen and other peripheral features, participants wore goggles, which limited the visual field to 65° (h) x 59° (v) of angle. 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 1000Hz at 100dB) were played at random intervals throughout the exposure duration. Communication with the participants during exposure was via a microphone.

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 (figure 1). A red (fixation) dot (0.57° of visual angle) was projected at eye height in the centre of the screen.

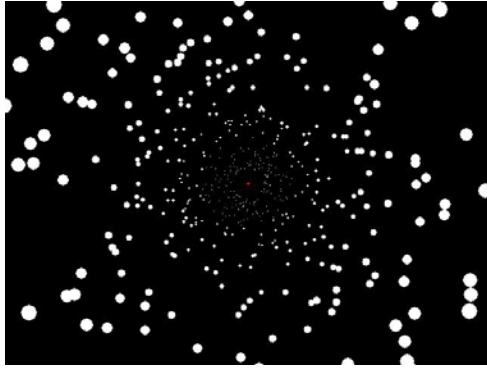


Figure 1. Sample frame of the optic flow pattern.

Three optic flow patterns were used. *Condition R*: oscillating roll motion was simulated by sinusoidal rotation of the random dot pattern around the anteroposterior axis at a frequency of 0.2 Hz (peak-to-peak amplitude of 120°, average angular velocity of 48°/sec).

Condition FB: radially expanding/contracting displays simulated sinusoidally oscillating forward and backward linear motion along the anteroposterior axes 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 display oscillated at a frequency of 0.2 Hz with an average peak angular velocity of 34°/sec.

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

Participants were exposed to each of the three conditions for 20 mins, and trials were separated by at least 24 hrs 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 pattern until they reported a compelling sensation of vertical linear self-motion. This typically occurred after about 15 seconds. When they indicated that they fully understood the task, the experiment commenced.

Motion sickness symptoms were assessed using the Simulator Sickness Questionnaire (SSQ) (Kennedy et al., 1993). Measures of interest were the change (post – pre exposure score) in the SSQ total scores and the change in the SSQ subscores (N, O & D) usually evaluated (Kennedy et al., 1993).

Participants rated the severity of their motion sickness every minute on Bagshaw and Stott's (1985) 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 mins, whichever was the sooner. Participants who reached a malaise rating of 4, and stopped, before 20 mins 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

Likert scale were anchored as ‘not at all’ (1) and ‘very much so’ (7). In conditions FB and RFB, as well as making this overall (o) rating, participants additionally evaluated vection magnitude in the individual directions that constituted the optic flow pattern: forward (F), backward (B) and roll (R). 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. Correlations between different groups of measurements were assessed by Spearman’s rho. Significance level was set to 0.05 for all tests.

Results

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

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 time course of mean sickness ratings, and the proportion of participants reporting vection, are both shown in figure 2. Whereas in conditions R and FB the mean sickness ratings (top) steadily increased over time, an unusual drop in mean sickness rating was observed in condition RFB. Inspection of individual’s data showed this trend to be consistent across participants.

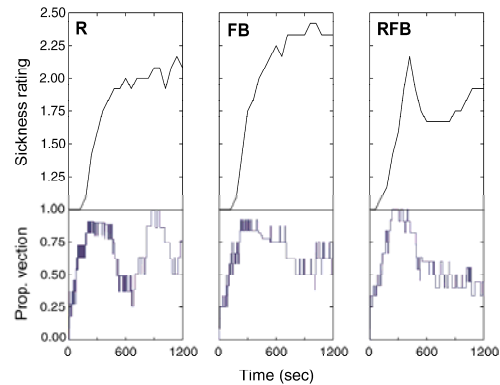


Figure 2. Mean sickness ratings (top) and proportion of participants reporting vection (bottom) as a function of time for each of the three conditions (Roll (R), Forward-Backward (FB), Roll + Forward-Backward (RFB)).

Figure 3a shows the mean accumulated sickness rating for each condition. The accumulated sickness rating in condition RFB was slightly lower than in conditions R and FB. None of the differences were statistically significant however.

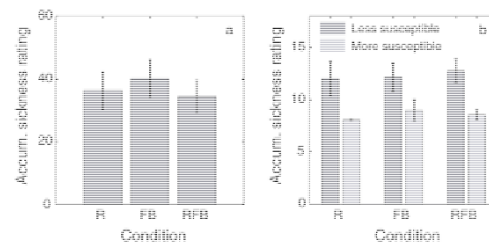


Figure 3. (a) Mean (\pm SEM) accumulated sickness rating for each condition over the complete trials (20 mins). (b) Mean (\pm SEM) accumulated sickness ratings for the two susceptibility groups over the first 420 secs.

To investigate whether the failure to find an effect of the experimental manipulation can be explained by the adaptation that appears to have occurred in condition RFB (figure 2), the first 420 seconds of the accumulated sickness ratings were analysed further. The sickness rating accumulated over this period was found to be only slightly higher in condition RFB than in the other conditions but none of the differences was significant.

To examine the possibility that the effect of the experimental manipulation was masked by differences in susceptibility between participants, a third analysis was performed in which participants were separated into a “more susceptible” and “less susceptible” group. The “more susceptible” group consisted of the eight participants who reported a sickness rating of 3 (mild nausea) during at least one of the three conditions. The remaining four participants formed the “less susceptible” group. The accumulated sickness ratings based on the first 420 seconds (before any adaptation was seen) as a function of susceptibility are shown in figure 3b. In the “more susceptible” group, the accumulated sickness rating in condition RFB was slightly higher than it was in conditions R and FB. However, the effect was small and failed to reach the required significance level. A similar result was seen when sickness rating onset was examined.

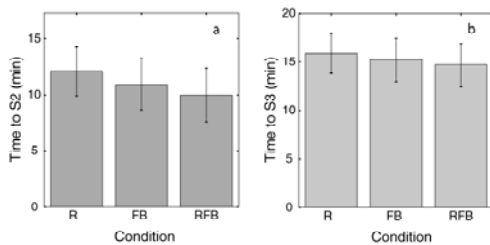


Figure 4. (a) Mean (\pm SEM) time to sickness rating 2 (S2). (b) Mean (\pm SEM) time to sickness rating 3 (S3).

Time to sickness ratings 2 and 3 are shown in figure 4a and 4b, respectively, for all twelve participants. Differences in time to sickness rating 2 and 3 between conditions were small and none were found to be significant.

Simulator Sickness Questionnaire:

The SSQ total scores and the SSQ subscores N, O, and D showed no significant differences between the conditions.

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.

Figure 5 shows the mean vection magnitude ratings for each condition overall (o) and for each of the individual directions separately. The overall magnitude was highest in condition R, followed by conditions FB and RFB. Wilcoxon Signed Ranks tests demonstrated the overall vection magnitude in condition R to be significantly higher than in condition RFB ($p < 0.05$). This was consistent with participants' reports that in condition RFB vection was mainly perceived in the anterior-posterior axis (i.e. forward – backward self-motion). Finally, backward vection was rated lower in condition RFB compared with condition FB, although this difference was not significant.

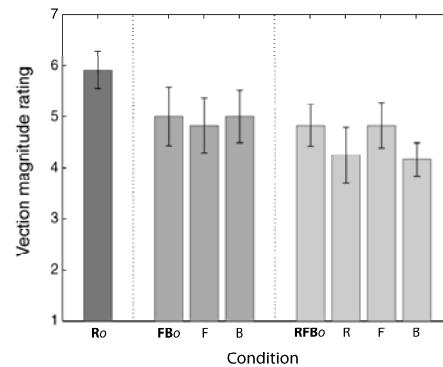


Figure 5. Mean (\pm SEM) vection magnitude ratings (1-7) for each condition overall (Ro, FBo and RFB) and individual directions (R = Roll; F = Forward; B = Backward).

The mean percentage of the total exposure duration that vection was reported was shorter in condition RFB (56%) than in condition FB (66%) and R (67%). However, these differences did not reach the level of significance required. Mean vection onset time was highest in condition FB, followed by condition R and RFB but the differences were not statistically significant.

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 (sec)
R	.539	.206	-.011
FB	.403	-.029	.124
RFB	.591*	-.025	.188
Pooled	.702*	-.179	.164

* Significant at the 5% level

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.

Discussion

The purpose of this study was to investigate whether dual-axis motion would elicit more VIMS than single-axis motion. Remarkably, exposure to dual-axis motion (i.e. combined rotational and translational motion) did not increase the level of VIMS compared with exposure to its constituent parts in isolation despite the apparent additional sensory conflict. These 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 (e.g. Oman, 1982, 1991; Reason, 1978) and suggest rotational and translational motion to be combined in a non-linear fashion.

Initially sickness ratings in all conditions gradually increased over time by similar amounts. However, in 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 nauseating visual stimulus (e.g. Hettinger & Riccio, 1992; Hill & Howarth, 2000; Hodder & Howarth, 2003; Kennedy et al., 2000), and that during trials individuals will, on occasion, report decreases in symptom magnitude as well as

increases, this *mean* decrease is a novel finding.

A clue to an explanation for the unexpectedly low level of VIMS during dual-axis motion is found in the observation that the overall vection magnitude tended to be lower during dual-axis motion than during single-axis motion patterns. Andre et al. (1996) observed a similar effect in that vection was experienced as less compelling when observers were exposed to the more complex pattern in which the stripes were tilted. If the degree of VIMS is a consequence of vection magnitude, then if the combined stimulus RFB does not produce vection which is equivalent to the addition of the components FB and R, one would not expect an equivalent increase in VIMS.

In this context, it is of interest to refer to a study by Freeman and Harris (1992) in which the detection of expansion was found to be unaffected by the presence of rotation, and vice versa. Taken together with the existence of expansion- and rotation-selective neurons in area MST (e.g. Bruce et al., 1981; Sakata et al., 1985; Tanaka et al. 1989; Tanaka & Saito, 1989), the visual system thus appears to contain mechanisms selective for expanding or rotating optic flow that function independently of each other in the analysis of complex retinal flow.

The possibility of "mutual suppression" between R and FB in the current study suggests that at least with regard to vection, different mechanisms may be engaged that are not independent of each other. Further support for this notion comes from the observation that compound vection (i.e. simultaneous rotational and translational vection) occurs when two flow vectors are summed, but not when two flow vectors are simply overlaid at the same depth plane (Ito & Fujimoto, 2003). When vertical and circular flows were overlaid, perceptual bistability occurred and only one flow induced vection at a given time. As pointed out by Ito and Fujimoto (2003), if both flow vectors would be processed in parallel, a

similar compound vection would have been expected to occur in the overlay condition.

In our study, unlike that of Ito and Fujimoto (2003), vection duration was shortened during dual-axis motion compared with the single-axis motion patterns. This apparent discrepancy can be explained by the difference in exposure duration between their study (120 secs.) and ours (1200 secs.) because the decrease in the proportion of our participants reporting vection occurred after about 420 seconds.

Adaptation has previously been shown to occur during prolonged stimulation for both linear (Berthoz et al., 1975) and circular vection (Brandt et al., 1974) as manifested by a steady decrease in vection velocity. However, the present results also indicate that the rate of adaptation may not be homogeneous across axes as the adaptation rate tended to be lower during linear motion, which, from an ecological perspective, may not be surprising.

The temporal correspondence between the time course of vection and sickness rating, as well as the strong correlations between vection magnitude and motion sickness, suggest a causal relationship between vection and motion sickness. However, a similar decrease in vection was observed in condition R without a concomitant decrease in mean sickness rating. Inspection of the individual trial records shows that i) the onset of symptoms is always preceded by the occurrence of vection, but may linger on after vection has dissipated, and ii) participants who do not experience motion sickness may nevertheless experience compelling sensations of vection. Vection therefore appears to be a necessary precursor of visually induced motion sickness (see also Hettinger & Riccio, 1992), whereas individual differences in sensitivity to sensory conflict may determine whether or not motion sickness occurs.

Conclusion

Dual-axis motion did not increase the level of motion sickness compared with

single-axis motion, despite apparent additional sensory conflict. This finding is inconsistent with VIMS being determined by simple summation of the provocative stimuli, and suggests that rotational and translational motion stimuli are not independently processed.

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