



The effect of visual motion stimulus characteristics on vection and visually induced motion sickness[☆]

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ARTICLE INFO

Keywords:

Optic flow
Self-motion
Speed
Density
Axis rotation
Cybersickness
Simulator sickness
Virtual reality

ABSTRACT

Several factors contribute to the likelihood of experiencing illusory sensations of self-motion (i.e., vection) in Virtual Reality (VR) applications. VR users can also experience adverse effects such as disorientation, oculomotor issues, or nausea known as visually induced motion sickness (VIMS). The goal of the present study was to systematically investigate three characteristics of visual motion stimuli—speed, density, and axis of rotation—and how they relate to both vection and VIMS. Two experiments were conducted. In Experiment 1, a stereoscopic stimulus containing a star field of white spheres on a black background was presented to 21 participants. The stimulus contained linear forward motion (expanding optic flow) and was varied with respect to (a) speed (faster, slower) and (b) density (lower, higher). Ratings of vection (onset time, intensity, duration), VIMS (measured via FMS, SSQ), and presence were recorded. In Experiment 1 vection was found to be strongest under faster and higher density conditions. VIMS was overall minimal and not affected by either speed or density. In Experiment 2, rotation along the pitch, yaw, or roll axes were added to the stimulus that created the strongest vection in Experiment 1, resulting in spiral/curvilinear motion profiles. Again, subjective ratings of vection, VIMS, and presence were collected. Results showed that vection intensity was significantly increased when pitch or roll rotation were added to forward motion. Despite overall low VIMS scores, pitch rotation resulted in the highest FMS scores and significantly greater disorientation as measured by the SSQ. No correlations between the vection and VIMS measures were observed. Overall, these results suggest that all three stimulus' characteristics (density, speed, added rotations) can alter the sensation of vection and can have additive effects, but that this increase in vection is not necessarily associated with increases in VIMS.

1. Introduction

It is desirable across many Virtual Reality (VR) applications for users to experience a rich and compelling sense of self-motion through space, even when they are not physically moving – a sensation commonly referred to as vection [1,2]. It is, however, also critical to ensure that VR applications do not inadvertently introduce adverse side effects known as simulator sickness or visually induced motion sickness (VIMS [3–5]); symptoms of which include discomfort, disorientation, oculomotor issues, or nausea. Indeed, optimizing this balance is one of the most significant challenges of modern VR systems development, given that VR setups capable of inducing compelling vection often also have

the capacity to induce strong adverse side effects [4]. There are many known factors that are associated with the likelihood of experiencing vection and/or VIMS. These include, for instance, the size of the field-of-view [6–8], the availability of stereoscopic depth cues [9–12], and the presence of multisensory stimulation (e.g., auditory, tactile, vestibular) [2,4,13–19]. Further critical factors to consider are the characteristics of the virtual environment (VE) itself, such as the photo-realism of the display, scene complexity/density, the presence of depth cues, the inclusion of foreground and background information, the type of movements simulated (e.g., translational, rotational), and the speed of movement (see [20–22] for reviews). Notably, some of these factors have primarily been evaluated in the context of vection and others

[☆] This paper was recommended for publication by Richard H.Y. So.

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<https://doi.org/10.1016/j.displa.2018.07.005>

Received 18 April 2018; Received in revised form 18 July 2018; Accepted 24 July 2018

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primarily in the context of VIMS, but rarely has the joint effect of these characteristics on both vection and VIMS been systematically evaluated together (see sections below for several notable exceptions). In fact, the associations between vection and VIMS are complex and there are unique experimental design considerations associated with studying each independently (see [4] for a review). In addition, particular characteristics of VEs and visual motion stimulus parameters that might affect vection and/or VIMS are most often studied independently of each other and interactions among these parameters are consequently not well understood. Therefore, in this study we investigated the effects and possible interactions of three particularly relevant parameters of visual motion stimulation and the interactions among them on the experience of both vection and VIMS, including (1) stimulus speed, (2) stimulus density, and (3) movement type (i.e., axis of rotation during spiral/curvilinear movements). Below we will briefly summarize the current literature with regards to each of these characteristics and their relation to vection and VIMS.

1.1. Visual stimulus speed

Many studies over the years have demonstrated that increased visual stimulus speed typically leads to increased vection and VIMS, up to a certain stabilizing threshold [20,23,24]. For instance, So et al. [25] used a natural scene stimulus to measure translational vection and VIMS across eight different speed intervals ranging from 3 m/s to 59 m/s. They demonstrated that both vection and nausea increased from 3 m/s to 10 m/s before plateauing. When using an optic flow display on the ground surface, Tamada and Seno [26] also observed increased vection intensity ratings with increased speed (from 0 to 1.5 m/s across 5 intervals). Using an optokinetic drum to induce rotational vection, Bubka et al. [27] demonstrated that VIMS increased with faster compared to slower rotational speeds (–10 vs. 5 rotations per minute). In addition, our previous work demonstrated that an increase in the rotational speed of a static scene from 60 m/s to 90 m/s resulted in stronger perceptions of circular vection along the yaw axis [28], corroborating earlier work showing a vection-enhancing effect of increasing stimulus speed [6,20,23,29–31]. Importantly, in most of these studies, stimulus speed was the main manipulation of interest and therefore, the interaction effects of speed with other visual motion parameters remain largely unknown.

1.2. Visual stimulus density

While extremely sparse visual images are unlikely to induce a strong and compelling sensation of vection, increased content density and more highly contrasting features are associated with more robust experiences of self-motion [20,22,29,32]. For instance, Lubeck et al. [32] presented participants with dot stimuli that included both a foreground and background pattern that differed in both density and movement status (stationary or rotating in roll). Their results demonstrated that vection was stronger when rotation was perceived in the background and when the moving dot densities were higher. Overall, however, to our knowledge only a few studies have investigated the role of stimulus density on VIMS specifically. For instance, Palmisano and colleagues demonstrated that more optic flow was associated with greater VIMS [33] (see also [34]). However, nothing is known about how density interacts with other visual motion parameters apart from depth order to affect each vection and/or VIMS.

1.3. Visual axis rotation

Different axes of physical rotation stimulate the vestibular organs in unique ways and each type of rotational motion differs in the extent to which it is experienced during typical, everyday behaviours (see Rebenitsch and Owen [35] for a review). For instance, motion about the yaw axis stimulates the horizontal semicircular canals whereas pitch

motion stimulates the superior semicircular canals and roll the posterior semicircular canals. Yaw is also the most common type of sustained rotation experienced by humans compared to sustained pitch or sustained roll rotations, both of which are less common. These different axes of motion may therefore introduce different types and levels of sensory conflict and/or anticipated co-stimulation between visual and vestibular inputs [36–38], thereby resulting in differing levels of vection and VIMS. However, very few studies have directly compared both vection and VIMS across all axes of rotation.

Bubka and Bonato [39] added varying levels of tilt to their optokinetic drum to introduce off-axis motion (5° or 10° tilt) and demonstrated that VIMS was higher under the tilted condition relative to gravitational upright and was even higher for tilts of greater magnitude (an effect that was exacerbated with fluctuating changes in speed). Diels and Howarth [40] presented participants with linear visual motions (fore-aft), rotational motion in the roll axis, and both motions combined. They measured VIMS and vection and reported that neither measure was greater in the combined motion condition relative to the single axis motion conditions. In fact, in the combined translational plus rotational condition, VIMS decreased at longer durations (after 500 s). Vection was more intense for pure rotation compared to combined rotation plus translation.

Several other studies have compared two of the three axes of rotation with each other (e.g., roll vs. pitch) or analyzed the additive effects of combining motions across multiple rotational axes [40–42]. For instance, a study by Keshavarz and Hecht [43] compared rotations in pitch alone, versus pitch + roll, versus pitch + roll + yaw. In that study VIMS ratings were lower for the single axis motion compared to the dual and triple axis motions. Lo and So [25] are the only investigators, to our knowledge, who compared all three axes of rotation to each other. In their study they presented participants with an image of a virtual street scene, which they rotated in either the pitch, roll, or yaw axis. Their results demonstrated no differences in VIMS across any of the rotational axes. Vection scores were not reported.

Of note is that no previous studies have compared each axis of rotation when co-present with translational movement components (i.e., curvilinear or spiral motion). Given that, under most natural conditions the eyes/head move with six degrees of freedom, understanding how these combined motions relate to vection and VIMS is an important extension of this research.

1.4. Current study

All of the abovementioned studies differed substantially with respect to the nature of the setups employed and the nature of the VEs, ranging from optokinetic drums to large projection displays, from optic flow stimuli to natural scenes, from translational movements to rotational or curvilinear movements, from short exposure times to long exposure times, and from vision fixated to free field vision conditions. Therefore, it becomes difficult to determine the extent to which these visual motion stimulus parameters affect vection and VIMS when controlling for all other likely contributing factors. Consequently, in the current study we manipulated three particular parameters of the VE (stimulus speed, stimulus density, and axis rotation) while keeping all other factors constant (i.e., display type, instructions, task constraints). Considering and manipulating all three parameters together allowed us to determine their respective effects on vection and VIMS while avoiding other confounds. This approach also allowed us to investigate potential interactions among these factors on both vection and VIMS, which has previously not been explored.

Here we used a large field-of-view stereoscopic projection display to present an optic flow star field stimulus. In Experiment 1 the stimulus was moving linearly using forward translations and in Experiment 2 rotations were added such that simulated forward translations were combined with rotations in yaw, pitch, or roll. Star field optic flow stimuli have the advantage of providing the capacity to strategically

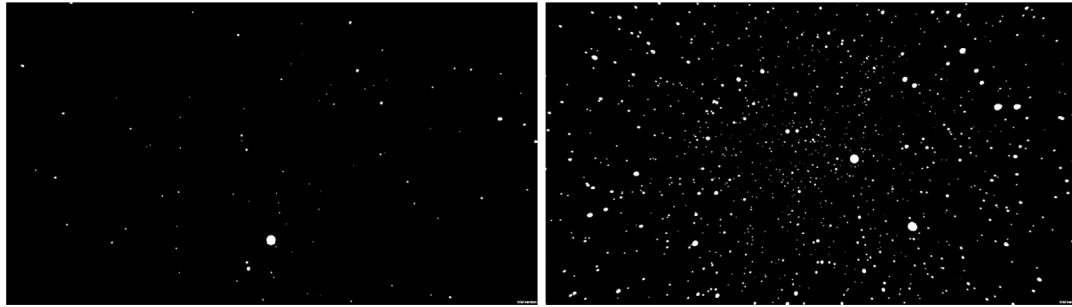


Fig. 1. Screenshots of Experiment 1 stimuli with low density on the left and high density on the right.

manipulate particular parameters of the visual motion information, compared to, for instance, complex natural scenes. In Experiment 1 we systematically manipulated stimulus speed (slower; 15 m/s, vs. faster; 75 m/s) and stimulus density (lower density vs. higher density) to evaluate their individual and combined/interactive effects on both vection and VIMS. Based on previous findings, we expected faster stimulus speed and higher stimulus density to increase vection ratings and reduce vection onset times. Moreover, we also expected to find an additive effect of these two stimulus parameters, resulting in increased vection when the stimulus was moving faster *and* contained higher density. Additionally, the concept of presence (defined as “being there” in a virtual environment, [45]) has been shown to correlate with vection [44], and we therefore predicted that participants experiencing stronger vection would also experience increased presence. With respect to VIMS, we predicted either a positive correlation or no correlation with vection; if vection was positively related to VIMS, one could expect increased VIMS in the conditions where vection was strongest. However, given that the relationship between vection and VIMS is complex (see [4]), it is possible that VIMS will remain unaffected across the different experimental conditions. In Experiment 2 the axis of rotation was systematically manipulated so that the motion profile included forward motion plus either pitch, yaw, or roll axis motion, resulting in curvilinear motions for pitch and yaw, and spiraling motions for roll. Based on the findings of previous studies (e.g., [39–43]), we predicted that adding axis rotation would lead to stronger vection and VIMS ratings compared to linear motion alone. In contrast, we had no directional hypotheses about whether/how vection and VIMS would differ across yaw, pitch, and roll rotation.

The results from Experiment 1 were used to determine the stimulus parameters (i.e., speed and density) for which the maximum level of vection was reported and were then implemented for the stimulus used in Experiment 2 upon which the axis manipulations were then applied. In both experiments the dependent variables included subjective measures of vection (onset time, intensity, duration), VIMS (real-time using the Fast Motion Sickness Scale and after stimulus exposure using the Simulator Sickness Questionnaire), and presence.

2. Experiment 1

2.1. Methods

2.1.1. Participants

Twenty-one participants aged 18–40 years voluntarily took part in the experiment, all of whom gave written consent prior to assessments and experimental procedures. One participant’s data was removed from the analyses due to substantially higher baseline sickness scores before the experiment started (i.e., FMS baseline score of 5). The final sample size consisted of 12 male participants ($M_{\text{age}} = 24.1$, $SD_{\text{age}} = 6.77$) and 8 female participants ($M_{\text{age}} = 19.37$, $SD_{\text{age}} = 1.4$), all with normal or corrected-to-normal visual acuity (minimum score of 20/25 on a Snellen Visual Acuity Chart). Participants reported to be healthy with no illness, no history of stroke or dementia, and no musculoskeletal,

cognitive, psychiatric, or vestibular impairments at the time of participation. The study was approved by the University Health Network’s research ethics board. Participants received compensation of \$10 per hour. Participants were free to terminate the experiment at any time without penalty. No participant stopped the experiment prematurely.

2.1.2. Design, apparatus and stimuli

The study was conducted in a dark room with no windows. Participants were seated in a height-adjustable, rotating chair 200 cm away from a projection screen 300 cm wide and 196 cm tall, resulting in a field-of-view (FOV) of 74° horizontally and 53° vertically. The height of the chair was adjusted individually to maintain an eye-height of approximately 140 cm above the ground.

Using Unity3D (Unity Technologies, 2015), four sequences of randomly arranged white dots were generated on a black background in a seemingly infinite virtual environment (“star field”, see Fig. 1 and Supplemental Videos). At initialization, three-dimensional dots were uniformly placed at random within the volume of a virtual bounding sphere. The number of dots was either set to 200 or 5000, while the volume of the virtual bounding sphere was held constant (radius = 1500 m), resulting in two random dot stimuli with varying densities (lower and higher). Forward velocity was set to either 15 m/s (slower) or 75 m/s (faster). Translational transitions were applied to the camera object, simulating forward, linear motion at a constant velocity without an acceleration or deceleration phase. To create the illusion of distance, the colour of the dots were blended to gradually match the background color as a function of distance relative to the active camera, rendering objects in far distance (approx. 780 m) invisible. With every updated frame, the distance between each dot and the camera was calculated and objects outside the virtual bounding sphere were removed and repositioned at a random location on the surface of the virtual bounding sphere, resulting in a constant density of dots. No radial motion or jitter was added to the constant velocity linear motion. The stimuli were presented stereoscopically using shutter glasses (Optoma GT750E projector; side-by-side mode); this was achieved by creating a second active camera object that was aligned relative to the first with a fixed distance of 6.4 cm to account for an average inter-pupillary distance. Each of the two cameras rendered alternating images for the left and the right eye. The sides of the shutter glasses were covered with black cloth to limit the FOV to only the projection screen. Each trial was 8 min long without interruption. Even though this stimulus length is in excess of what is typically required to induce vection, this duration was chosen to provide sufficient time for potential VIMS to build up within each trial. Further, because we were targeting the modulating effects of different stimulus parameters on vection and VIMS, it was important to avoid floor or ceiling effects for either measure (i.e., fully saturated vection or intense VIMS). Inducing high levels of VIMS was also avoided to reduce potential carry-over effects between conditions given the importance of the within-subject design used here.

All participants completed all four experimental trials once (higher density/slower speed, lower density/faster speed, higher density/faster

speed, lower density/slower speed) in a counterbalanced order to control for carry-over effects¹. Consequently, this resulted in a 2×2 within-subject design including the factors stimulus density (lower vs. higher) and stimulus speed (slower vs. faster).

2.1.3. Response measures

Three different vection measures were collected, including vection onset time, vection intensity, and vection duration. Vection onset time was communicated verbally by the participants when they first felt vection (regardless of vection intensity), which was recorded in seconds. Vection intensity was measured on an 11-point Likert scale (0 = no vection at all, 10 = very strong vection), indicating how strong the sensation of vection was that participants perceived. Vection duration was rated verbally in percent (with 0% meaning that they did not perceive vection at all and 100% meaning that they felt vection throughout the whole trial), indicating how long the subjective sensation of vection lasted once it was perceived. Vection intensity and duration were collected at the end of each of the four trials. In addition, self-reported ratings of presence (i.e., the feeling of “being there” in the virtual world, see Heeter et al. [45]) were also collected using an 11-point Likert scale (0 = no presence at all, 10 = very strong presence).

VIMS was measured in two ways. First, the Simulator Sickness Questionnaire (SSQ, [46]) was used to assess the various symptom clusters of VIMS. The SSQ is a standardized questionnaire containing 16 items that are each rated on a 4-point Likert scale ranging from “not at all” to “severe”. Three subscales—nausea (SSQ-N), oculomotor (SSQ-O), and disorientation (SSQ-D), as well as a total score (SSQ-TS) were calculated using pre-defined factor weightings. The SSQ was administered once prior to the experimental trials (baseline) and once after each of the four trials. Second, the Fast Motion Sickness Scale (FMS), a verbal rating scale ranging from 0 (no sickness) to 20 (severe sickness), was administered once before each trial and once every minute throughout stimulus exposure. The FMS was designed to specifically capture the nausea and discomfort aspect of simulator sickness in real time [47] and may therefore be more sensitive to sensations experienced in the moment. The peak FMS score can be interpreted as the maximum feeling of nausea and discomfort experienced during stimulus exposure and has been shown to strongly correlate with the SSQ subscales and the SSQ total score [15,47,48].

2.1.4. Procedure

All participants provided written informed consent prior to the study. Before the actual experiment began, the SSQ was completed to ensure that participants were not experiencing any sickness prior to stimulus exposure. Vection was described to the participants using a common real-life situation (“train analogy”), in which a person sitting in a stationary train experiences the sensation of self-motion when another stationary train waiting alongside starts moving. Subsequently, a practice and benchmarking trial was used to further familiarize participants with the task and the sensation of vection. As such, a stimulus was chosen that was expected to reliably induce vection and was comprised of a 30 s presentation of a constant forward motion with added roll motion (5000 dots presented at 10 m/s²), resulting in helical visual movement. All participants reported that they understood the concept of vection during the practice trial. After the practice trial, the four experimental trials were presented in a counterbalanced order. Vection onset time was verbally reported by the participants as soon as they started to experience vection. Vection intensity, vection duration, presence, and the SSQ were all collected after each trial. The FMS was administered once before each trial and once every minute throughout stimulus exposure to capture participants’ level of nausea. A rest break was provided between the trials. After the final trial, participants were

debriefed, compensated, and released by the experimenter once all VIMS-related symptoms had subsided to baseline.

2.2. Results

For data analyses of Experiments 1 and 2, the Statistical Software for Social Sciences (SPSS, IBM v.22) was used. A-priori significance level was set to $\alpha = .05$.

2.2.1. Vection and presence measures

A 2×2 repeated-measures (rm) ANOVA including the within-subjects factors stimulus speed (slower, faster) and stimulus density (lower, higher) was calculated for vection onset time, vection intensity, vection duration, and presence. For those trials in which vection was not reported at all, the maximum time (480 s) was recorded as the onset time². Table 1 shows the distribution of participants who did or did not experience vection for each trial type. Results for vection onset time, vection intensity, vection duration, and presence are shown in Fig. 2.

Vection occurrences. A Chi-squared test (Friedman) for non-parametric data did not reveal a significant effect of vection occurrences, $\chi^2(3) = 7.29, p = .063$, indicating no differences with respect to the number of participants who experienced vection among the four stimulus conditions.

Vection onset time: No significant effect of stimulus density, stimulus speed, or interaction effect was observed for vection onset time (p 's all $> .05$).

Vection duration: For vection duration, a significant main effect of stimulus speed, $F(1, 19) = 7.553, p = .013, \eta_p^2 = .284$, was observed, indicating that the faster stimulus created prolonged vection compared to the slower stimulus. There was no main effect of stimulus density and no interaction effect was observed.

Vection intensity: Significant main effects of stimulus density, $F(1, 19) = 11.270, p = .003, \eta_p^2 = .372$, and stimulus speed, $F(1, 19) = 14.801, p = .001, \eta_p^2 = .438$, were observed for vection intensity, indicating that vection was stronger when the stimulus had a higher density and faster speed. No interaction effect was observed.

Presence: For presence, significant main effects of stimulus density, $F(1, 19) = 5.444, p = .031, \eta_p^2 = .223$, and stimulus speed, $F(1, 19) = 4.729, p = .042, \eta_p^2 = .199$, were observed, indicating a stronger sense of presence for the higher density and the faster speed conditions. No interaction effect was observed.

2.2.2. VIMS measures

A 2×2 rm ANOVA including the within-subjects factors stimulus speed (slower, faster) and stimulus density (lower, higher) was calculated for the peak FMS score (i.e., highest FMS score reported during stimulus exposure), as well as each of the SSQ subscales nausea, oculomotor, disorientation, and the SSQ total score (see Fig. 3). The rmANOVA revealed no main effects of stimulus density or stimulus speed or interactions for any of the VIMS measures, including the peak FMS score and all of the SSQ subscales (p 's $> .276$).

To determine whether the visual stimuli induced VIMS at all, simple contrast comparisons were separately calculated for each of the SSQ subscales to obtain differences between the baseline scores and the four experimental trials. Results showed significantly increased SSQ ratings after each of the four experimental trials for all SSQ subscales compared to baseline (p 's $< .020$).

¹ One-way repeated-measures ANOVAs did not reveal any order effects for any of the dependent measures (p 's from .195 to .956)

² Note that the results of the statistical analyses did not change when participants who did not experience vection in all of the four trials were removed from data analyses ($N = 9$). We therefore decided to include these participants' data and set the onset time to 480s for those trials in which vection was not experienced.

Table 1

Number (percentages) of participants who did or did not experience vection during each of the four experimental trials.

	Stimulus speed			
	Faster		Slower	
	Higher density	Lower density	Higher density	Lower density
Vection	19 (90.5%)	16 (76.2%)	15 (71.4%)	13 (61.9%)
No vection	2 (9.5%)	5 (23.8%)	6 (28.6%)	8 (38.1%)

2.2.3. Relation between vection, presence and VIMS

To investigate whether/how ratings of vection, presence, and VIMS were related, Pearson correlations were calculated for all vection measures (onset time, duration, and intensity), presence, and VIMS measures (peak FMS score, SSQ subscales) for each of the four experimental conditions. Only small to moderate, non-significant correlations between VIMS and any of the vection and presence measures were found (ranging from $r = -.369$ to $r = .236$). Significant correlations were found between some of the vection measures and presence and are

given in Table 2. Results suggest that for the faster motions (which had shown enhanced vection in terms of intensity and duration in the above analysis) increasing vection intensity and duration were positively correlated with higher presence ratings, confirming our hypothesis and corroborating earlier findings [44]. Note that no such relation was found for the slower and less vection-inducing condition.

3. Experiment 2

The results of Experiment 1 demonstrated that higher stimulus density and faster stimulus speed resulted in greater vection intensity and greater presence, confirming our hypotheses. Higher density was also associated with longer vection durations. With regards to VIMS measures, while each stimulus demonstrated greater VIMS relative to baseline, VIMS ratings were overall quite low, and there were no differences in VIMS ratings associated with differences in density or speed. Therefore, we used the results of Experiment 1 to identify the stimulus that resulted in the greatest level of vection (higher density, faster speed) and applied three separate axes of rotations to investigate any further effects of rotational movements on vection, presence, VIMS, and presence beyond that contributed by the parameters evaluated in

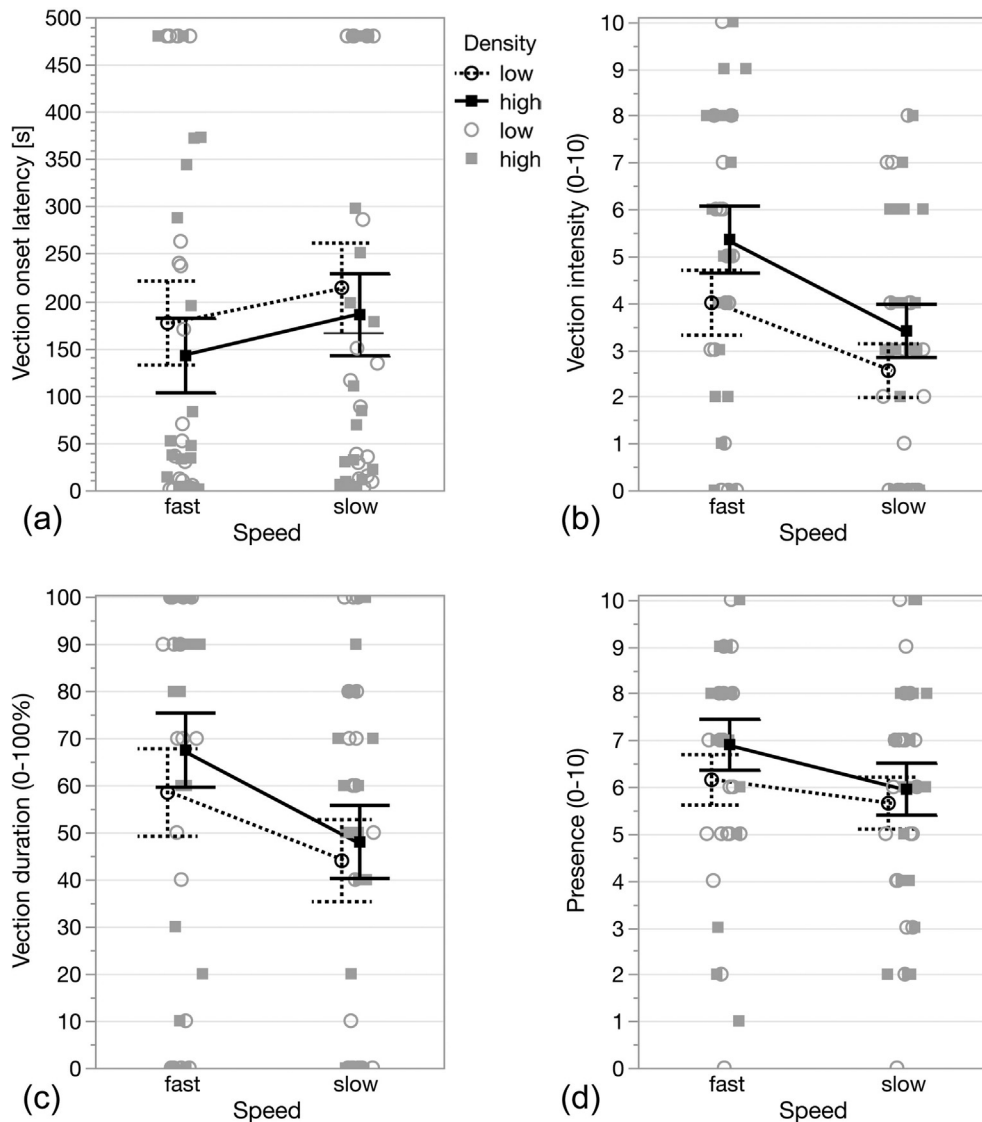


Fig. 2. Average scores for vection onset time (A), vection intensity (B), vection duration (C), and presence (D) for the four experimental conditions separated by stimulus speed and stimulus density. Error bars indicate SEM. Gray squares and circles represent individual participant's responses for the high and low density conditions, respectively.

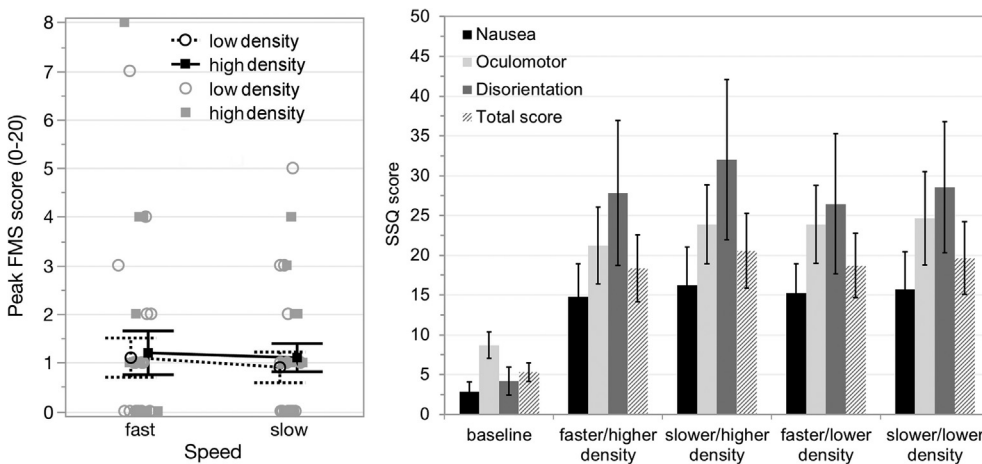


Fig. 3. Mean peak FMS scores reported across all four conditions (left panel) and average scores for all SSQ scores including baseline measures (right panel), separated by stimulus speed (faster, slower) and stimulus density (higher, lower). Error bars show SEM. Gray squares and circles represent individual participant's responses for the high and low density conditions, respectively.

Table 2
Pearson correlations (r) between presence and vection separated by stimulus parameter conditions.

Stimulus parameters	Vection measure		
	Onset time	Intensity	Duration
Faster, higher density	-.059	.630**	.578**
Faster, lower density	.033	.540**	.569**
Slower, higher density	-.236	.130	-.003
Slower, lower density	-.072	.279	.255

Note:

** $p < .01$.

Experiment 1. Specifically, constant rotations along the yaw, pitch, and roll axes were added to the linear motion resulting in spiral/curvilinear motion. We assumed that adding rotational motion would increase vection and VIMS compared to pure linear motion, and consequently might also result in more pronounced associations between vection and VIMS. While particular differences among the three rotational motions were not strongly predicted, it might be expected that more common types of sustained rotations (i.e., yaw) would be associated with increased vection and/or increased VIMS due to the increased plausibility of this type of motion. Specifically, it is possible that since humans frequently experience certain types of sustained rotations (e.g., yaw motion), but very infrequently experience other types of sustained rotations (e.g., roll or pitch motion) that this increased familiarity with a particular motion profile may result in greater susceptibility to illusory self-motion compared to highly unfamiliar/atypical motions. This could result from the brain's interpretations of statistical regularities in our interactions with our world. An alternative prediction is that more common motions may also be more prone to perceiving sensory conflicts due to their well-established predictability and anticipated co-stimulation of visual-vestibular inputs, in which case reduced vection and increased VIMS might also be observed. It is also possible that because visual yaw rotations do not conflict with the gravity vector, whereas pitch and roll do, that this might predict less vection for pitch and roll and more VIMS compared to yaw.

3.1. Methods

3.1.1. Participants

Twenty-two new participants aged 18–36 years voluntarily took part in this experiment. Due to incomplete data, one participant's data was removed from the analyses. Thus, the final sample size consisted of 11 male participants ($M_{age} = 24.36$, $SD_{age} = 6.31$) and 10 female

participants ($M_{age} = 22.50$, $SD_{age} = 3.69$)³, all of whom gave written informed consent prior to all assessments and experimental procedures. All participants had normal or corrected-to-normal visual acuity (minimum score of 20/25 on a Snellen Visual Acuity Chart). Participants reported to be healthy with no illness, no history of stroke or dementia, and no musculoskeletal, cognitive, psychiatric, or vestibular impairments at the time of participation. The study was approved by the University Health Network's research ethics board and participants received compensation of \$10 per hour for their participation. Participants were free to terminate the experiment at any time without penalty, however, no participants stopped the experiment prematurely.

3.1.2. Design, apparatus, and stimuli

To investigate the influence of axis rotation on vection and VIMS, a one-factorial within-subjects design was chosen; this involved the factor axis rotation with four levels (pitch, yaw, roll, none). The visual stimulus that generated the strongest vection in Experiment 1 (i.e., linear motion with higher density and faster speed) was selected for Experiment 2 and modified with respect to axis of motion. That is, rotation either along the pitch, yaw, or roll axis was added to the pure linear forward motion, resulting in spiral motion for roll trials and curvilinear motions for pitch and yaw trials. The speed of rotation was set to 5 deg/s for each axis rotation. The condition without axis rotation was added as a control and as a replication of the condition in Experiment 1 that created strongest vection (high density, faster speed), resulting in a total of four trials, each presented for 8 min without interruption. The experimental setup was identical to Experiment 1 (room, projector setup, shutter glasses, etc.).

3.1.3. Procedure and response measures

The procedure and response measures were identical to Experiment 1. Again, The SSQ was collected at baseline, followed by the same, brief practice trial. The four experimental trials, each including a different axis of rotation (pitch, yaw, roll, none), were then presented in an order counterbalanced across participants to account for carry-over effects⁴.

³ To investigate sex differences, vection and VIMS measures were combined for the stimulus condition that was identical in both experiments (i.e., high density and high speed condition in Experiment 1, no rotation condition in Experiment 2). This resulted in a total of 23 male and 19 female participants. Independent samples t tests (Bonferroni corrected) revealed no sex differences for any of the vection measures (p 's $> .050$) or any of the VIMS measures (p 's $> .434$).

⁴ One-factorial repeated-measures ANOVAs showed an order effect for vection duration, $F(3, 63) = 4.465$, $p = .007$, $\eta_p^2 = .175$, with post-hoc tests indicating that vection was significantly longer during the 4th trial compared to the first two trials. No other order effects were observed.

Table 3

Number (percentage) of participants who did or did not experience vection during each of the four axis rotation trials.

	Axis rotation			
	Yaw	Pitch	Roll	No rotation
Vection	19 (86.4%)	19 (86.4%)	18 (81.8%)	16 (72.2%)
No vection	3 (13.6%)	3 (13.6%)	4 (18.2%)	6 (27.3%)

FMS scores and vection onset time were collected during each trial. Vection intensity, vection duration, presence, and the SSQ were recorded verbally after each trial. At the end of the experiment, participants were debriefed and compensated, after which the experimenter ensured that all VIMS-related symptoms had subsided to baseline.

3.2. Results

3.2.1. Vection and presence measures

The number of participants who did and did not experience vection in each of the four trials is given in Table 3. A one-factorial rmANOVA including the within-subject factor axis rotation (pitch, yaw, roll, none) was conducted for vection onset time, vection intensity, vection duration, and presence (see Fig. 4). Degrees of freedom were Huynh-Feldt corrected (ϵ) if the assumption of sphericity was violated.

Vection occurrences. A Chi-squared test (Friedman) for non-parametric data did not reveal a significant difference with respect to the number of participants who experienced vection among the four rotation conditions. That is, the added rotations did not significantly change the number of participants experiencing vection (see Table 3).

Vection onset time. A significant effect of axis rotation was observed for vection onset time, $F(3, 60) = 3.117, p = .039, \eta_p^2 = .135, \epsilon = .879$. Simple contrast comparisons showed that the no rotation condition yielded significantly longer vection onset latencies than the conditions with added rotations in yaw ($p = .037$), pitch ($p = .033$), and roll ($p = .037$), confirming the hypothesis that adding rotations would enhance vection.

Vection intensity. A significant effect of axis rotation was found for vection intensity, $F(3, 60) = 3.188, p = .037, \eta_p^2 = .137, \epsilon = .879$. Simple contrast comparisons showed that vection intensity was significantly lower in the no rotation condition compared to pitch ($p = .016$) and roll ($p = .011$) rotation, but not compared to yaw rotation ($p = .082$).

Vection duration and presence. No significant effect of axis rotation was observed for vection duration or presence, although Fig. 4(c) shows a trend towards higher vection duration for the conditions that included axis rotations compared to the no rotation condition as predicted.

3.2.2. VIMS measures

One-factorial rmANOVAs including the within-subject factor axis rotation (pitch, yaw, roll, none) were conducted for the peak FMS score and the SSQ subscales nausea, oculomotor, disorientation, and the total score (see Fig. 5). Degrees of freedom were Huynh-Feldt corrected (ϵ) if the assumption of sphericity was violated.

Peak FMS scores. A significant effect of axis rotation was found for the peak FMS score, $F(3, 60) = 3.110, p = .042, \eta_p^2 = .135, \epsilon = .844$. Post-hoc comparisons (Bonferroni-adjusted $\alpha = .0125$) revealed significantly higher FMS scores during pitch rotation compared to no rotation ($p = .011$). No other comparisons were significant (p 's $> .024$).

SSQ measures. A significant effect of axis rotation was observed for the SSQ subscale disorientation, $F(3, 60) = 3.918, p = .019, \eta_p^2 = .164, \epsilon = .839$. Post-hoc comparisons (Bonferroni adjusted $\alpha = .0167$) revealed significantly higher disorientation scores for pitch compared to yaw ($p = .002$) and pitch compared to no rotation ($p = .015$), but not for pitch compared to roll rotation ($p = .089$). No further significant differences between any other axes of rotation were found. No effect of

axis rotation was found for the SSQ subscales nausea, oculomotor, and the total score.

To determine whether the visual stimuli induced VIMS at all, simple contrast comparisons were separately calculated for each of the SSQ subscales to compare the baseline scores with the scores for the four axis rotations. Results showed significantly higher SSQ scores after each of the four conditions compared to baseline for all SSQ subscales (p 's $< .018$).

3.2.3. Relation between vection, presence, and VIMS

Pearson correlations were calculated for all vection measures (onset time, duration, and intensity), presence, and all VIMS measures (peak FMS score, SSQ subscales) for each of the axis rotation conditions and are summarized in Table 4. Overall, only small to moderate, non-significant correlations between VIMS and any of the vection or presence measures were found (ranging from $r = -.335$ to $r = .379$). Significant correlations were found between some of the vection measures and presence and are given in Table 4. That is, for added pitch and roll (but not yaw or no rotations) participant who experienced stronger vection also reported higher presence.

3.2.4. Comparison between Experiment 1 and Experiment 2

The VIMS scores (peak FMS score and SSQ scores) as well as the vection measures (intensity, duration, onset time) of the no rotation condition of Experiment 2 were compared with the identical condition of Experiment 1 (high density/high speed condition) using t tests for independent samples (Bonferroni adjusted $\alpha = .005$). VIMS scores did not differ between the two groups (p 's $> .234$). A trend for vection duration was observed ($p = .026$), suggesting longer vection durations in Experiment 1 (67.5%) compared to Experiment 2 (37.6%). No other differences in vection measures were observed (p 's $> .215$). Interestingly, the rates of vection were lower in Experiment 2 (72.2%) compared to Experiment 1 (90.5%). This was likely due to the fact that the no rotation trial in Experiment 2 was embedded in trials for which pitch, yaw, and roll rotations were introduced. This may have resulted in relative comparisons among the trials, which potentially led to a lower relative rating for the no rotation trial compared to Experiment 1, where all other comparisons included no rotation (except for the practice trial that included roll rotation). It can be assumed that the introduction of rotations resulted in at least some increased sense of vection, which the patterns do suggest (rates of 86.4%, 86.4% and 81.8% for yaw, pitch, and roll respectively). This is an important observation given that, generally speaking, across studies and across participants, subjective ratings are likely influenced by relative comparisons; hence we emphasized the importance of comparing all parameters within one study and with the same participants.

4. General discussion

The results of the present study demonstrated differential effects of visual stimulus characteristics (density, speed, and axis of rotation) on ratings of vection, VIMS, and presence. We will discuss each of the findings associated with each of the research objectives and their implications.

4.1. Visual stimulus speed and density

The first objective of the current study was to understand the additive or interactive effects of particular visual motion stimulus characteristics (stimulus density and stimulus speed) on vection, VIMS, and presence. In terms of vection and presence, higher visual stimulus density and faster visual speed resulted in greater vection intensity and greater presence. Higher visual stimulus density was also associated with longer vection durations. Interestingly, the effects of density and speed were found to be additive with respect to vection intensity ratings and presence. As such, the results support the findings of previous

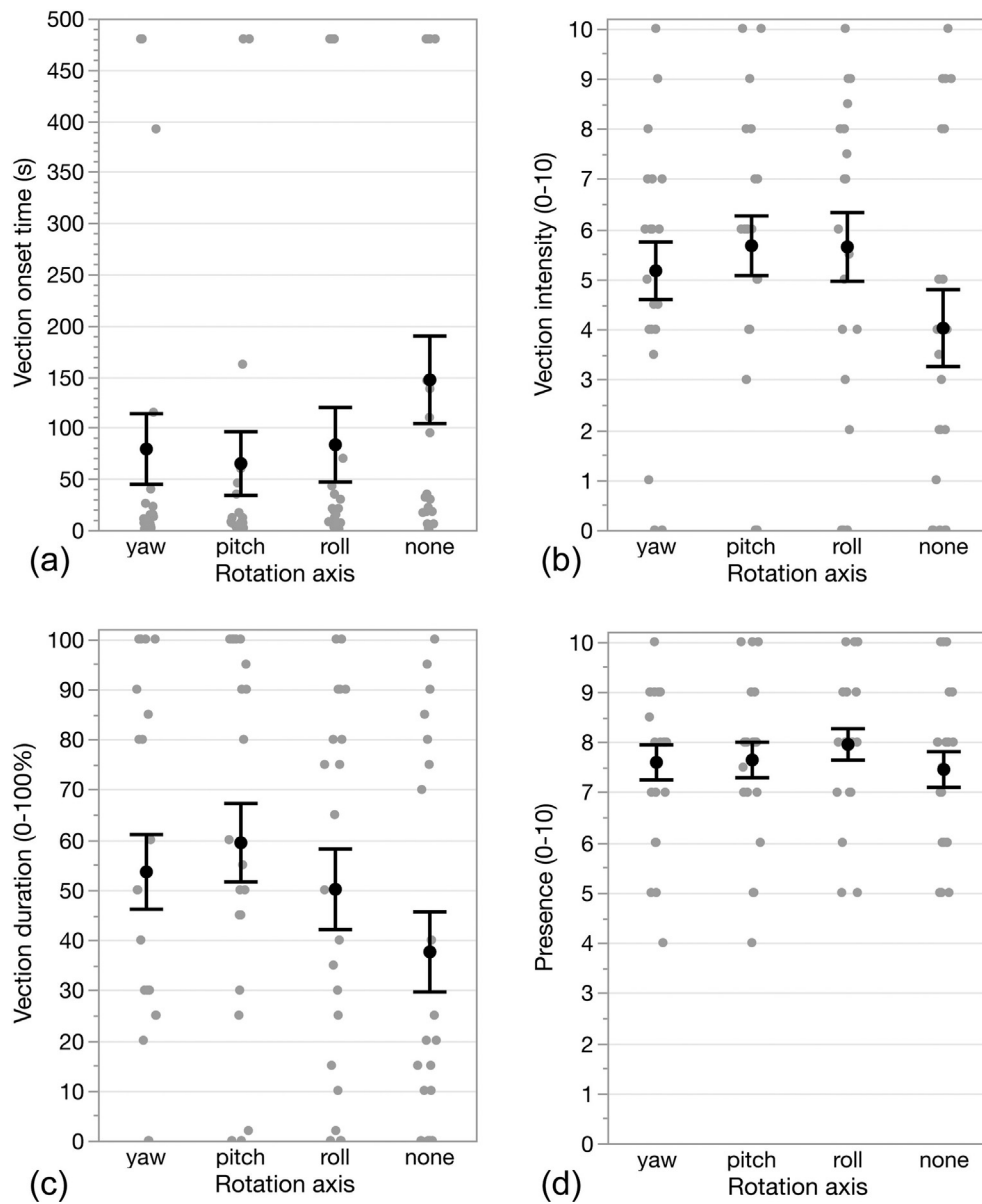


Fig. 4. Average scores for vection onset time (A), vection intensity (B), vection duration (C), and presence (D) for the four experimental conditions separated by stimulus speed and stimulus density. Error bars indicate SEM. Gray dots represent individual participant's responses.

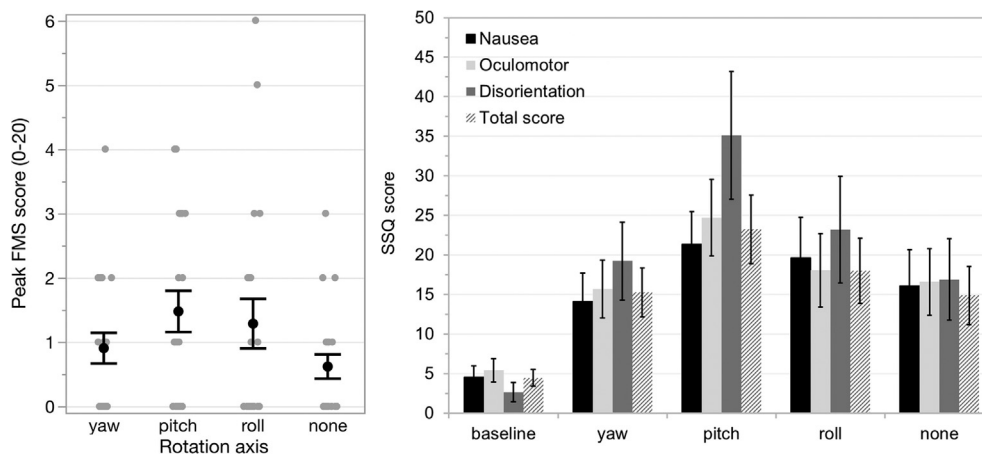


Fig. 5. Mean peak FMS scores reported (left panel) and average scores for all SSQ scores including baseline measures (right panel), separated by axis rotation. Error bars indicate SEM. Gray dots represent individual participant's responses.

Table 4
Pearson correlations (*r*) between presence and vection separated by axis rotation.

Axis rotation	Vection measure		
	Onset time	Intensity	Duration
Yaw	-.344	.212	.369
Pitch	-.263	.552**	.517*
Roll	-.376	.619**	.445*
No rotation	-.309	.269	.189

Note:

* $p < .05$.

** $p < .01$.

studies indicating that speed and density individually increase the experience of vection [20,23–25,32]. However, the novel finding here is that combining these two factors increased vection even further. Of course, the nature and magnitude of these effects are likely dependent on other factors such as the type of the stimulus and display. For instance, even larger effects may be observed for more naturalistic scenes with more cues to depth and distance for which speed and angular motion may be better scaled. Also, because the range of the stimulus parameters that were sampled in the current study was narrow (i.e., two speeds and two density levels), it is possible that these effects may be different at smaller or more extreme values in either direction along this continuum. In terms of VIMS measures, every stimulus introduced at least some level of VIMS (albeit weak) relative to baseline. However, there were no differences in VIMS ratings associated with density or speed. This is not consistent with previous findings that have suggested that stimulus speed can affect the severity of VIMS [25,49]. For instance, Hu and colleagues [23] used an optokinetic drum to induce VIMS and found significantly more VIMS when the drum rotated at faster speeds. With respect to stimulus density, higher amounts of optic flow have also been suggested to increase VIMS [24,50]. However, given the overall very low VIMS ratings (particularly in the peak FMS scores) reported in the present study, it is difficult to ultimately draw conclusions about whether stimulus density and speed and the combination of the two affect VIMS. To further investigate this, a stronger, more nauseating stimulus that can be systematically varied in density and speed is required. However, what can be concluded is that density and speed can differentially affect vection and VIMS within the stimulus properties examined here.

4.2. Visual axis rotations

While the mere introduction of visual rotational motions affected vection compared to pure translational movements (rotations generally resulted in faster onset times and greater intensities), the specific type of axis rotation (i.e., pitch vs. yaw vs. roll) was not strongly associated with differentially influences on vection ratings. One interesting result was that vection intensity ratings did not differ between yaw rotations and no rotations, even though pitch and roll were significantly higher than no rotations. This suggests that perhaps yaw may be unique and supports the prediction that motions more commonly experienced in everyday life, when presented purely visually, may be less able to induce illusions of self-motion.

With respect to VIMS, the introduction of pitch resulted in the highest FMS scores and significantly more disorientation as measured by the SSQ compared to both no rotation and yaw rotation. It is not immediately clear why pitch might be unique in this respect and such effects have not been previously observed. For instance, Lo and So [51] who compared all three axes of rotation separately did not find differences with respect to VIMS among the rotation types. Studies combining rotations across multiple axes have typically found increased VIMS when rotations along more than one axis were provided

[41,50,52,53], suggesting that additive influences of different axis movements may have a more pronounced effect on VIMS than single axis motion.

4.3. Relationship between vection, VIMS, and presence

The second main objective of the study was to evaluate whether the effects of modifying visual motion stimulus parameters would affect vection and VIMS ratings in ways that were similar or divergent. It is important to note that our stimuli successfully induced vection, but only generated low scores of VIMS as observed in the peak FMS scores (but not in the SSQ scores). The interpretation of the relationship between vection and VIMS is therefore limited to some extent by these circumstances and conclusions based on the current results should be drawn carefully. Nevertheless, the results of our study demonstrated that vection and VIMS measures did not appear to be strongly associated for the stimuli tested in this study. Specifically, the increases in vection that were observed with changing stimulus parameters (higher density and faster speed) were not associated with increases in VIMS. Further, differences in vection observed for different axis rotations (i.e., greater intensity for pitch and roll vs. no rotation but not for yaw vs. no rotation) were not similarly associated with differences in VIMS. In general, the relationship between vection and VIMS is complex (see [4] for a review) with several studies indicating that vection is a relevant and/or necessary contributor to VIMS [14,54–57] and others reporting no correlation between the two [58–61]. The current study provides support for the idea that, within the range of stimulus parameters introduced and manipulated here and the associated limitations, any parameter-associated differences observed were not the same for vection and VIMS. With respect to the relationship between vection and presence, strong and positive correlations were found, suggesting that the two concepts are linked to each other [44]. However, this finding was not consistent across all conditions, making further investigations desirable to better understand how vection and presence are related to each other.

4.4. Limitations of the study

A more conservative approach was used to select the values of the stimulus parameters implemented in the current study because we intentionally avoided introducing ceiling effects for vection (i.e., fully saturated vection) in order to be more sensitive to any (even subtle) modulating effects of the various visual stimuli parameters. Similarly, stimuli were selected to intentionally avoid introducing significant symptoms of VIMS for the same reason and to avoid strong carryover effects that could mask any more subtle stimulus-related effects. However, as mentioned previously, the VIMS ratings were, in fact, closer to floor effects given that ratings were overall low in the peak FMS score and did not appear to be strongly modulated by the stimulus parameters apart from the introduction of rotational motion (primarily pitch). Therefore, it may be the case that either these specific parameters do not influence VIMS, or that modulating effects to VIMS were not observed because the range of the parameter levels tested were not well-aligned with those that would be more likely to lead to VIMS. Note, however, that the SSQ scores observed in the present study suggested an induction of VIMS that could be considered meaningful. For instance, Lubeck et al. [32] reported that SSQ scores can be elevated even when static images are presented. The SSQ scores found in our study, in contrast, exceed the level of VIMS induced by static images in Lubeck et al. on average by a SSQ total score of 15. Nevertheless, conclusions regarding potential relationships between vection and VIMS need to be drawn very carefully. To overcome this issue in future studies, stimulus duration could be prolonged (up to 30 min) or be made more VIMS-inducing by adding more accelerations, and/or different experimental conditions could be tested on separate days. This would allow for the use of stimuli that induce stronger VIMS and yet

prevent carry-over effects. Also, future work could test these effects across a greater range of stimulus parameters or by using stimuli that are more likely to evoke greater sickness.

5. Conclusion

The goal of the present study was to systematically investigate three characteristics of visual motion stimuli—speed, density, and axis of rotation—and how they relate to both vection and VIMS. Results indicated that all three stimulus characteristics affected ratings of vection. Interestingly, the level of VIMS was not affected by the manipulation of any of the three characteristics. This finding suggests that certain characteristics of visual stimuli can alter the perception of vection without necessarily affecting the level of VIMS. In other words, our results demonstrate that vection can be experienced in the absence of VIMS. However, given the overall low VIMS ratings in both experiments, the precise relationship between the two constructs still needs further attention.

Funding

This research did not receive any specific grant from funding agencies in the public, commercial, or not-for-profit sectors.

Conflict of interest statement

None.

Appendix A. Supplementary material

Supplementary data associated with this article can be found, in the online version, at <https://doi.org/10.1016/j.displa.2018.07.005>.

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