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Effects of frame rate on vection and postural sway☆

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ABSTRACT

The quality of stereoscopic 3D cinematic content is a major determinant for user experience in immersive cinema in both traditional theatres and cinematic virtual reality. One of the most important parameters is the frame rate of the content which has historically been 24 frames per second for movies, but higher frame rates are being considered for cinema and are standard for virtual reality. A typical behavioural response to immersive stereoscopic 3D content is vection, the visually-induced perception of self-motion elicited by moving scenes. In this work we investigated how participants' vection varied with simulated virtual camera speed, frame rate, and motion blur produced by the virtual camera's exposure, while viewing depictions of movement through a realistic virtual environment. We also investigated how their postural sway varied with these parameters and how sway covaried with levels of perceived self-motion. Results show that while average perceived vection significantly increased with 3D content frame rate and motion speed, motion blur had no significant effect on perceived vection. We also found that levels of postural sway induced by vection correlated positively with subjective ratings.

1. Introduction

The quality of a motion picture image sequence depends on a number of factors including the spatial and temporal resolution of the images. The spatial resolution of digital cinema has been steadily improving. On the other hand, cinema frame rates have remained unchanged since the 1920s when they were standardized to facilitate stable audiovisual synchronization [1]. The resulting 24 frames per second (fps) standard was a compromise that provided acceptable visual quality under technical and economic constraints. While in most cases 24 fps was found to support the perception of continuous motion, such a low flash rate produces objectionable flicker in strobed displays. Therefore, when using a cinema projector, each frame is flashed two or three times to reduce flicker without increasing frame rate [2]. The universal adoption of the 24 fps standard has resulted in a particular expectation for motion quality in 2D and stereoscopic 3D (S3D) film, which is a large part of what is known as 'the film look'. This aesthetic distinguishes cinematic content from crisper content typical of higher frame rate applications like simulation, games and video.

Many believe that the enhanced fidelity provided by higher frame rate (HFR) capture and presentation has the potential to dramatically improve viewer experience [3,4]. The current low frame rate limits the fidelity of motion that can be portrayed and introduces motion artefacts such as strobing, motion blur, aliasing and judder, which are common in 24 fps content. In cinema these artefacts can be avoided since shots are planned and composed. However, avoiding these artefacts imposes restrictions on camera and subject motion, and thus limits the creative possibilities for the cinematographer. In unscripted, undirected content such as immersive virtual reality (VR) or gaming, the motion cannot be constrained in this way since it is determined in real time by the user's actions.

Self-motion is an important determinant of immersion in cinema and VR; and the camera is often moving from the subject's point of view. In immersive cinema, the viewer is usually stationary and seated while such motion is portrayed. In VR the user can physically move but in many cases (e.g., simulations of long distance travel) may be relatively still compared to the motion being portrayed. Nevertheless, the stationary or relatively still viewer in these scenarios may experience a compelling illusion of self-motion produced by the visual display that is known as vection [5,6]. Although the technical impact of HFR on motion quality has been widely recognized, there have been few attempts to assess its impact empirically and there have been no studies of

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the portrayal and experience of self-motion with realistic stimuli. The goal of the experiments reported here was to evaluate the impact of frame rate on vection using S3D movies. As outlined below, we consider variables that interact with frame rate to determine the degree of motion artefacts in film content: camera exposure and camera motion.

A stroboscopic motion picture sequence consists of a series of discrete still images which, in the case of a self-motion sequence, correspond to discrete camera locations at regular temporal intervals along the portrayed motion path. In a stereoscopic sequence two such related sequences are produced, one from the vantage point of each eye. The fidelity of the motion sequence depends critically on the temporal sampling rate (frame rate) and aliasing; other artefacts will arise if the temporal sampling rate is insufficient. Such sampling artefacts will be visible to the viewer if they fall within a range of spatio-temporal conditions identified as the 'window of visibility' [7,8]. Increasing the sampling rate pushes the potential artefacts outside the visible range, resulting in the percept of relatively smooth motion. When self-motion is portrayed, the motion stimulus is complex and will depend on the scene content, eccentricity, fixation, type and speed of camera motion and other factors. Thus, except in simplified scenes and simplified motion (for example, pure rotation) artefacts are likely to appear, or be more pronounced, in some parts of the image than in others. While much can be learned from these simplified conditions [9], it is important to assess the impact of frame rate using representative scenes and motion paths.

A potentially important determinant of vection is the apparent smoothness of the portrayed motion. Researchers have attempted to quantify the sample rate at which stroboscopic motion appears equivalent to continuous motion (or appears to be smooth and continuous). For example, Burr et al. [10] studied the effects of frame rate on the perception of drifting sinusoidal gratings. For the lowest spatial frequency grating of 0.07 cycles per degree moving at the fastest speed of 171 deg/s (temporal frequency of 12 Hz), the frame rate needed to be at least about 60 Hz to appear smooth to their two subjects. In a related study, De Bruyn and Orban [11] reported that the maximum velocity at which direction discrimination was possible increased with frame rate (at least until the highest frame rate of 100 fps that they tested). More recently, Kuroki et al. [12,13] found that perceived motion smoothness during free head/eye movement while viewing a high-refresh rate CRT improved with increased frame rate up to 250 Hz, at which point responses plateaued.

Another factor that may influence vection is motion blur. When exposure time is not infinitesimally short, the image moves across the sensor during the exposure period producing motion smear of the image or motion blur. Motion blur is a function of the image speed and the exposure duration of each frame. While mechanical shutters are no longer in use, it is still conventional to refer to the exposure duration in terms of the equivalent shutter angle. The typical shutter angle used for 24 fps footage is 180 deg, which is equivalent to the shutter being 'open' for half of the frame. The impact of both frame rate and shutter angle are modulated by image velocity. Motion artefacts caused by rapidly moving cameras or objects can be reduced by employing higher frame rates and smaller shutter angles. However, although the physical constraints of stroboscopic image sampling can be modeled, and blur can be quantified, there is evidence that these calculations do not accurately predict perceived blur [14,15]. Thus, here we assess the impact of various degrees of motion blur on vection.

There is a large literature on the effects of frame rate, refresh rate, and latency in interactive computer graphics applications such as vehicle simulation, human-computer interaction, gaming and virtual reality (VR). Most of this work has focused on the effects of very low frame rates (sub 10 fps) and so is not particularly relevant to film. For VR, frame rates are important; tasks such as heading perception are impacted below 15 fps for review see [16]. In interactive graphics, frame rate can be a limiting factor on response latency and long interaction latencies have a number of negative effects for review see [17]. Meehan et al [18] found that presence and physiological correlates such as heart rate in a stressful environment increased with frame rate from 15 to 30 fps consistent with a more compelling VR display. However, the physiological stress measures were unexpectedly high at 10 fps, which the authors attributed to discomfort and poor balance at this low frame rate.

There has been discussion of the effects of frame rate in cinema on vection and simulator sickness but, as for VR and gaming, most of this work has focussed on the effects of low frame rates [19]. However, a potentially relevant observation from this literature is that vection is increased by realism [20,21]. Given that higher-frame rate motion has been described as hyper-realistic it is possible that the compelling motion in HFR footage will increase the sense of vection particularly in immersive theatre scenarios. While negative reactions such as simulator/cinema sickness are usually associated with very low frame rates e.g., [22], the compelling motion may promote cinema sickness. Similarly, as the moving image becomes increasingly realistic the chances of experiencing uncanny valley and other negative reactions increase [23]. To our knowledge, there has been no investigation of these possibilities.

The experiments presented here are the first to empirically evaluate the impact of HFR, with synchronized capture and presentation, on vection elicited by S3D cinema content. Two experiments were conducted: in the first we investigated the effects of three S3D movie parameters on perceived vection strength (frame rate, stimulus motion speed and motion blur). In the second, we examined the effects of these parameters on perceived vection and on postural sway in response to perceived vection.

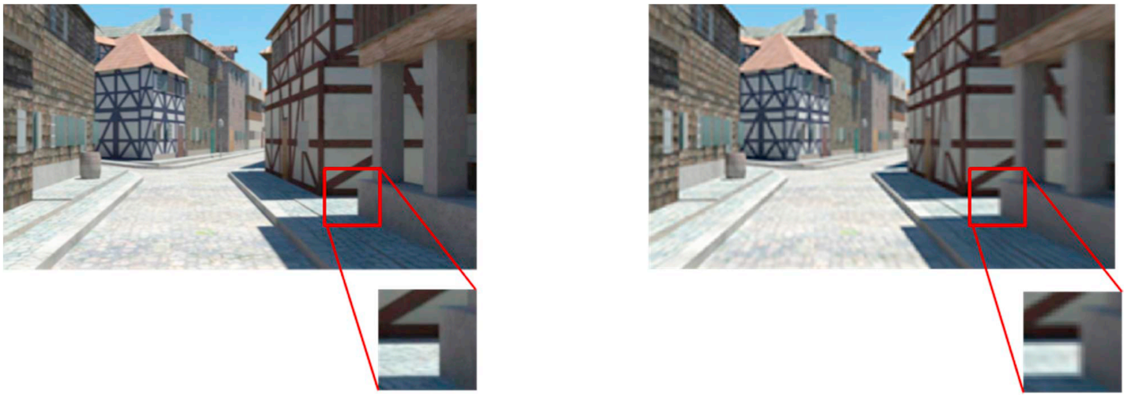
2. Methods

2.1. Participants

30 adult volunteers (including two experimenters) consisting of 17 females and 13 males ranging in age from 17 to 63 years participated in Experiment 1. They received $10 CAD after the experiment as an honorarium for participation. A second group of 32 adult volunteers (27 females and 5 males) ranging in age from 18 to 23 years participated in Experiment 2. They received credit in an undergraduate Psychology course for their participation. None (except for two experimenters who participated in Experiment 1) were aware of the purpose of the experiment. All observers agreed to avoid medication that would affect their stability while participating in the study and reported no relevant illness. Their participation was also based on a score of at least 80% in a random dot stereogram test. Results from 4 of the 32 participants in Experiment 2 were excluded from analysis; one of these did not understand the task, the other three exhibited excessive foot movement throughout the session which made their postural sway data unusable. Both studies were approved by the research ethics board of York University, Toronto, Canada.

2.2. Stimuli

Stimuli were 1920 × 1080 pixel stereoscopic 3D computer graphics movies which subtended 50 × 29 deg. They were rendered using computer graphics software (AUTODESK Maya, v2015 windows 64 bit). Movie sequences depicted forward motion (from the camera point of view) along a winding street in a medieval city [24]. At the start of each movie the scene was stationary, then motion accelerated for 5.0 s, after which a constant speed was maintained. The average speed was 20 or 40 km/h for the slow and fast motion conditions respectively. All movies were 30 s in duration. During rendering, the 3D camera positions were set to the height of the centre of the screen, the interpupillary distance (IPD) was fixed at 6.5 cm, and cameras were pointed in the direction of instantaneous motion. The field of view of the virtual camera matched the visual angle of the projection screen from the



(a) Simulated blur at 0 ms camera exposure

(b) Simulated blur at 33.3 ms camera exposure

Fig. 1. Two rendered frames of the stimulus showing motion blur corresponding to (a) 0 and (b) 33.3 ms camera exposure. Insets show expanded regions to illustrate increased blur at 33.3 ms exposure.

distance to the observer. Because the scene was accurately scaled, participants observed a geometrically correct life-sized city model (see Fig. 1). To introduce different levels of motion blur, a series of movies was generated with four virtual camera exposure durations (0, 16.7, 33.3 and 66.7 ms). For a given exposure, the amount of motion blur increases with increasing image motion speed. Motion blur could therefore be kept constant by doubling the speed and halving the exposure duration.

2.3. Apparatus

Stimuli were played back using RV v4.2.4 (Tweak's frame-accurate real-time presentation software) from a PC running a Windows 7 SP1 64-bit operating system, an Intel Core i7-2700K 3.5 GHz processor, 32 GB internal memory, and an NVidia Quadro K5000 graphics processing unit. They were presented as stereoscopic movies via a Christie Digital Mirage projector (Christie Digital Systems, Kitchener, Canada; Fig. 2a) and Christie Digital active 3D shutter glasses (upper Fig. 2c). The projector's total refresh rate was 120 Hz, with refresh rate per eye of 60 Hz. Movie frame rates were 60, 30, 15 fps for each eye. Multi-flash protocol, wherein the same frame image was presented multiple times – once for 60 fps, twice for 30 fps and four times for 15 fps per eye, was used to match the projector's refresh and movie frame rates and keep the total number of frames presented for a given speed constant.

Participants in the first experiment sat on a chair placed at a viewing distance of 3.26 m from a 3 × 1.8 m Stewart Film projection screen (Stewart Filmscreen, Torrance CA; Fig. 2b) and wore shutter glasses to view the S3D content. Participants in the second experiment stood on a 45 × 25 cm Nintendo Wii balance board (Nintendo Co., Ltd., Kyoto, Japan; Fig. 2d) placed at a distance of 3.26 m from the projection screen. To investigate the effect of visibility of the dimly lit surround observers viewed the stimuli under two conditions: (1) the shutter glasses without obstruction as in Experiment 1 and (2) the glasses enclosed within a periphery-occluding (PO) device made from cardboard (lower Fig. 2c). The PO device limited observers' periphery to the projection screen and blocked their view of the floor and the area surrounding the screen. An application developed by Brian Peek [25] was used to log centre-of-pressure (CoP) data transmitted from the Nintendo Wii balance board at 1 kHz nominal sampling frequency through a Bluetooth radio interface. Occasionally-dropped data frames were estimated through linear interpolation. A 101-length moving average filter was also applied to the data to reduce high frequency noise. Experiments were conducted in a large dark room where the only illumination was from the projected image. In both experiments, the head was not restrained but the subject was instructed to face the screen and remain still.

2.4. Procedure

In both experiments, a magnitude estimation procedure was used to measure the strength of perceived vection. In each trial, vection was rated relative to a standard stimulus that was shown to the observers at the beginning and at the midpoint of a session. The standard was the test movie with a frame rate of 30 fps, slow speed and camera exposure of 16.7 ms. Observers were told to assign '100′ to the vection they experienced when viewing the standard. In subsequent trials, they were asked to rate their perceived vection relative to that generated by the standard; for instance, if they experienced twice as much vection they would respond 200, half as much vection, 50. If no vection was experienced they were told to assign a value of 0. Prior to each trial, a white fixation cross was shown at the center of the black screen. The experimenter started a trial when the stimulus was loaded and the participant was ready. The fixation cross disappeared when the movie started, and after viewing the movie observers rated the strength of their perceived vection. In Experiment 1 ratings were recorded by the experimenter, and in Experiment 2 the participants made their responses using a wireless mouse and an onscreen keypad. Participants in Experiment 2 were asked to stand erect and relaxed on the balance board and to limit unnecessary movements (like shuffling of feet) that would corrupt the postural CoP data being collected.

In Experiment 1 each condition was presented once for each subject in random order for 2(speeds) × 3(frame rates) × 4(camera exposure) = 24 trials. In Experiment 2, we investigated the effect of eliminating screen edge and surround cues (along with frame rate and speed, and a fixed camera exposure of 33.3 ms) by having observers wear the PO device with the shutter glasses. Observers completed 6 trials corresponding to 2 speeds × 3 frame rates in each of two blocks, one block with and one block without their periphery occluded for a total of 12 trials. The order of blocks was counterbalanced and the order of trials within a block was randomized for each subject.

3. Results

The results of Experiments 1 and 2 are presented in Sections 3.1 and 3.2 respectively.

3.1. Results, Experiment 1

The graph in Fig. 3 shows the mean vection strength reported by the 30 participants in all 24 test conditions. Frame rates and camera exposure times are represented by their respective numerical values. Movie speed is indicated by letters S (slow) and F (fast). For example, 60-F-66.7 means the stimulus played back at 60 fps, with fast (40 km/h) motion speed and motion blur corresponding to a simulated camera

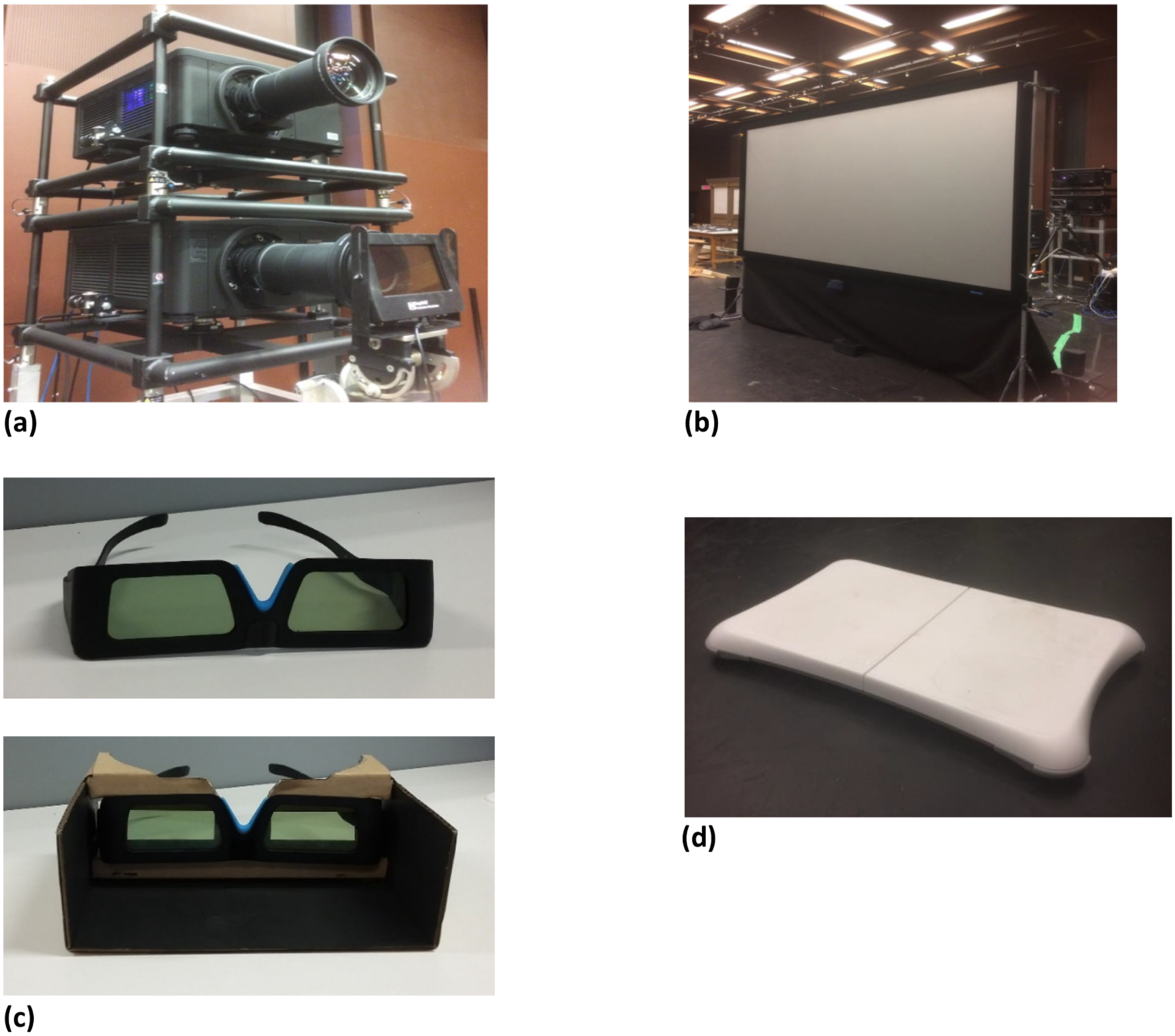


Fig. 2. Experiment apparatus (a) 1920 × 1080 pixel, 120 Hz refresh rate Christie Mirage projectors (only the upper projector was used) (b) 3 × 1.8 m Stewart Film projection screen (c) Christie Digital active 3D shutter glasses with (lower image) and without (upper image) the periphery-occluding (PO) device (d) Nintendo Wii balance board used to measure postural sway.

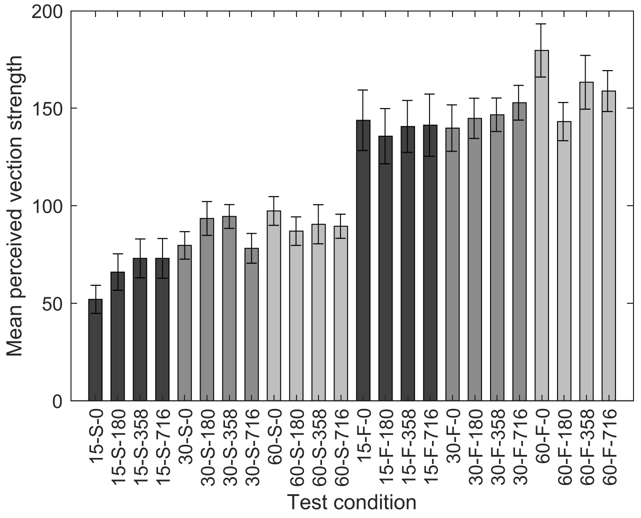


Fig. 3. Experiment 1 - mean vection strength reported by 30 participants for each frame rate, camera speed and exposure duration. Error bars represent ±1 standard error of the mean. See text for description of x-axis label convention.

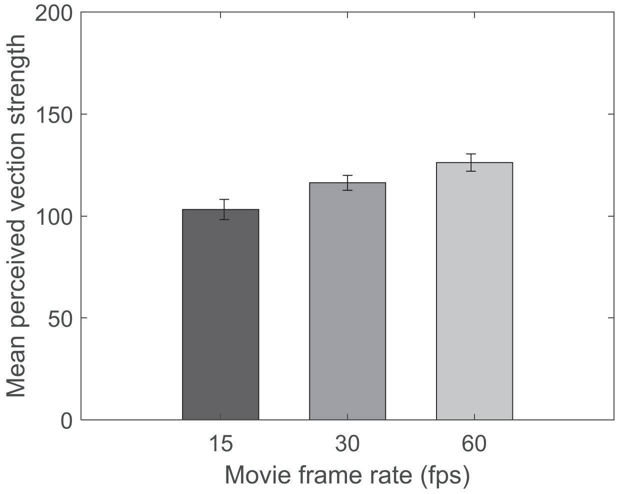


Fig. 4. Experiment 1 - effects of movie frame rate on mean perceived vection. Data are collapsed across camera motion speed and camera exposure. Error bars represent ±1 standard error of the mean.

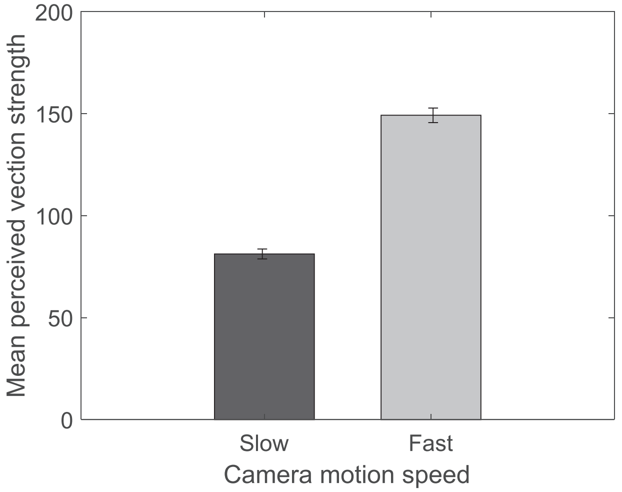


Fig. 5. Experiment 1 - effects of camera motion speed on mean perceived vection. Data are collapsed across movie frame rate and camera exposure. Error bars represent ±1 standard error of the mean.

exposure duration of 66.7 ms.

3.1.1. *Effects of stereoscopic movie parameters on perceived vection*

Figs. 4–6 show the mean perceived vection strength for movie frame rates of 15, 30 and 60 fps, slow and fast camera motion speeds, and camera exposure durations of 0, 16.7, 33.3 and 66.7 ms. A three-way Repeated Measures ANOVA (rANOVA) was used to assess main effects of and interactions between the movie parameters on perceived vection strength (see Table 1). Whenever the rANOVA revealed significant parameter effects on perceived vection strength, we used the Tukey's Honest Significant Difference Criterion (HSD) to identify the particular parameter levels that had statistically significant effects. We also evaluated effect sizes of the various movie parameters using *Partial Eta Squared* (partial Eta^2, η_p^2) given by the formula

$$\eta_p^2 = SS_{effect}/(SS_{effect} + SS_{Error}) \tag{1}$$

where SS_{effect} = Variance associated with an effect (movie parameter) and, SS_{Error} = Movie parameter's associated error.

(i) Main effects

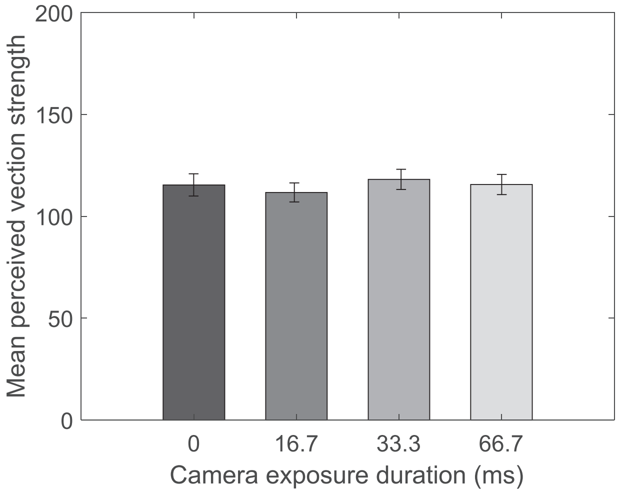


Fig. 6. Experiment 1 - effects of motion blur (simulated by the camera exposure duration) on mean perceived vection. Data are collapsed across movie frame rate and camera motion speed. Error bars represent ±1 standard error of the mean.

Table 1
Experiment 1, repeated measures analysis of variance for perceived vection magnitude. Results of the rANOVA test are shown, with the degrees of freedom (df), F-statistic, p values and effects size (partial Eta^2) specifying the effects of main movie parameters and their interactions.

Parameter	df (parameter)	df (error)	F	p	η_p^2
Movie frame rate	2	58	4.69	.013	0.106
Camera motion speed	1	29	54.9	< .001	0.608
Motion blur	3	87	0.909	.440	0.007
Movie frame rate & camera motion speed	2	58	2.02	.140	0.013
Movie frame rate & motion blur	6	174	2.38	.031	0.037
Camera motion speed & motion blur	3	87	1.80	.152	0.017
Movie frame rate & camera motion speed & Motion blur	6	174	0.67	.672	0.014

Movie frame rate: The rANOVA tested the hypothesis that the mean vection strength perceived at movie frame rates of 15, 30 and 60 fps were the same. The significant main effect shown in the first row of Table 1 suggests that mean vection strength varied significantly with frame rate (see Fig. 4). Tukey's HSD did not reveal any significant differences in mean vection estimates between pairs of frame rate conditions (Table 2).

Camera motion speed: The bar graph in Fig. 5 shows mean perceived vection strength at slow and fast camera speeds. Results of the rANOVA presented in Table 1 confirm that vection strength was significantly greater when viewing fast vs. slow moving stimuli.

Motion blur: The main effect of the four levels of camera exposure (0, 16.7, 33.3, and 66.7 ms) on vection was not significant, consistent with the relatively flat function depicted in Fig. 6. This suggests that motion blur had little direct effect on perceived vection.

(ii) Interaction effects

The effects of the two- and three-way interactions between movie parameters on mean perceived vection strength are also presented in Table 1. Of these, only the frame rate/motion blur interaction was significant. The result of Tukey's HSD across this interaction is shown in Table 3 and the corresponding interaction plot presented in Fig. 7. They show significant differences between frame rates of 15 and 60 fps, and 30 and 60 fps at only 0 ms camera exposure conditions. This interaction is difficult to interpret, but suggests that conditions with no motion blur were particularly effective at 60 fps but not at lower frame rates.

3.2. *Results, Experiment 2*

The bar graph in Fig. 8 shows the mean perceived vection strength reported by participants in all 6 conditions (consisting of 2 speeds × 3 frame rates) observed with and without peripheral occlusion.

3.2.1. *Effects of stereoscopic movie parameters and peripheral occlusion on vection strength*

The bar graphs in Figs. 9 and 10 show the effects of stimulus frame rate and motion speed on mean vection strength (n = 28). As in

Table 2
Experiment 1 - results of Tukey's HSD evaluating the impact of frame rate on perceived vection.

Frame rate		Lower bound	Upper bound	p
15fps	30fps	−31.8767	5.7517	.217
15fps	60fps	−46.2429	0.2845	.053
30fps	60fps	−21.8142	1.9809	.116

Table 3
Experiment 1 - results of Tukey's HSD evaluating effects of frame rate/motion blur interaction on perceived vection.

Frame rate		Camera exposure duration	Lower bound	Upper bound	p
15 fps	30fps	0 ms	−36.2585	12.59186	.465
15 fps	60 fps	0 ms	−63.6861	−17.4806	.0005
30 fps	60 fps	0 ms	−49.0871	−8.41286	.004
15 fps	30fps	16.7 ms	−44.5819	7.915264	.213
15 fps	60 fps	16.7 ms	−43.1807	14.68065	.453
30 fps	60 fps	16.7 ms	−13.5482	21.71489	.836
15 fps	30fps	33.3 ms	−35.2985	7.798502	.272
15 fps	60 fps	33.3 ms	−52.152	11.98533	.285
30 fps	60 fps	33.3 ms	−24.5016	11.8349	.669
15 fps	30fps	66.7 ms	−33.6524	16.98572	.698
15 fps	60 fps	66.7 ms	−44.2817	10.28168	.288
30 fps	60 fps	66.7 ms	−24.1218	6.78844	.362

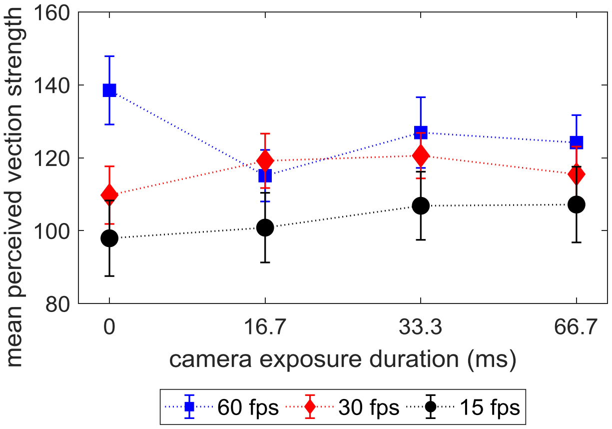


Fig. 7. Experiment 1 - illustrating effects of the interaction between movie frame rate and motion blur on perceived vection. Error bars represent ±1 standard error of the mean.

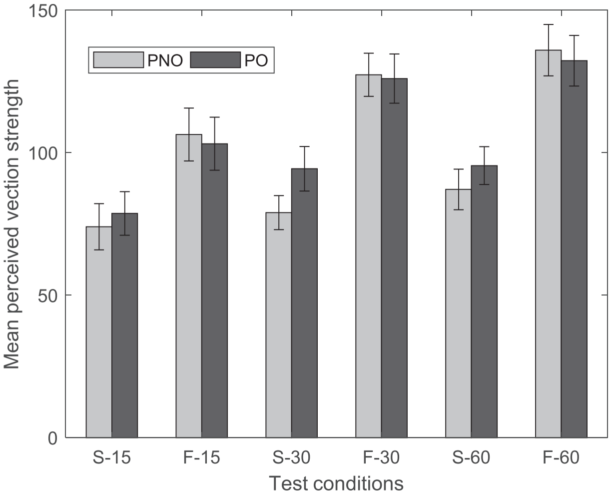


Fig. 8. Experiment 2 - mean perceived vection strength reported by participants in all periphery not occluded (PNO), (grey bars) and periphery occluded (PO), (black bars) test conditions. Error bars represent ±1 standard error of the mean. The letters in the labels stand for stimulus motion speeds (S = slow, F = fast) while numbers stand for the respective frame rates. All stimuli had a camera exposure duration of 33.3 ms.

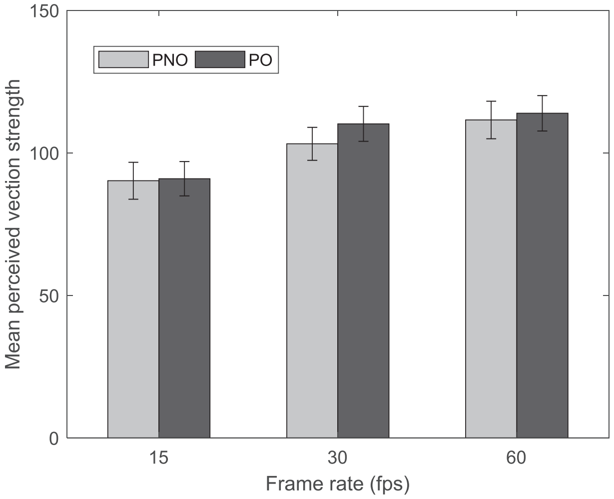


Fig. 9. Experiment 2 - effects of movie frame rate on mean perceived vection for periphery not occluded (PNO), (grey bars) and periphery occluded (PO), (black bars) conditions. Data are collapsed across camera motion speed. Error bars represent ±1 standard error of the mean.

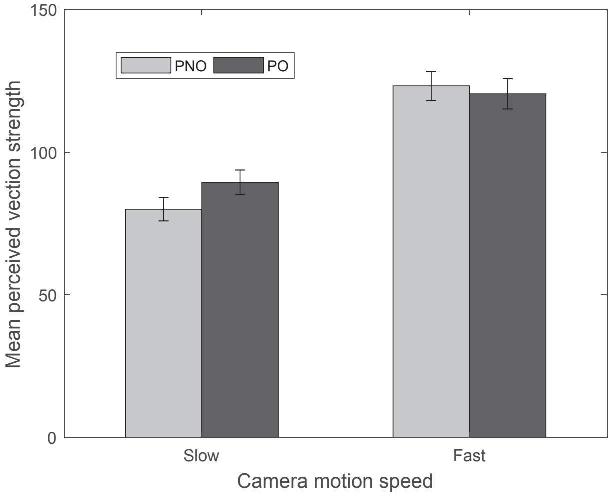


Fig. 10. Experiment 2 - effects of camera motion speed on mean perceived vection for periphery not occluded (PNO), (grey bars) and periphery occluded (PO), (black bars) conditions. Data are collapsed across movie frame rate. Error bars represent ±1 standard error of the mean.

Table 4
Experiment 2, repeated measures analysis of variance for perceived vection magnitude. Results of the rANOVA analysis, showing degrees of freedom (df), F-statistic, p values and effects size (partial Eta^2) for each stimulus parameter and their interactions.

Parameter	df (parameter)	df (error)	F	p	η^2
Movie frame rate	2	54	6.10	.004	0.192
Camera motion speed	1	27	40.0	< .001	0.484
Peripheral occlusion	1	27	0.54	.471	0.008
Movie Frame rate & camera motion speed	2	54	1.12	.333	0.026
Movie frame rate & peripheral occlusion	2	54	0.32	.727	0.005
Camera motion speed & peripheral occlusion	1	27	3.46	.074	0.025
Movie frame rate & camera motion speed & peripheral occlusion	2	54	0.13	.879	0.002

Table 5
Experiment 2 - results of Tukey's HSD evaluating the impact of movie frame rate on perceived vection.

Frame rate		Lower bound	Upper bound	p
15 fps	30 fps	−34.2250	2.0107	.089
15 fps	60 fps	−42.2762	−2.0095	.029
30 fps	60 fps	−13.6717	1.6002	.142

Experiment 1 we used a three-way rANOVA to assess main effects of and interactions between the various parameters on perceived vection strength (see Table 4).

(i) Main effects

Movie frame rate: As is evident in Fig. 9, similar to Experiment 1, there was a significant main effect of frame rate; vection responses generally increased with frame rate. Tukey's HSD revealed significant differences in mean perceived vection strength between stimulus frame rates of 15 and 60 fps but not between 15 and 30 fps or between 30 and 60 fps (Table 5).

Camera motion speed: Fig. 10 shows that vection responses were on average larger for the high speed condition than the low speed condition, consistent with a significant main effect of speed.

Peripheral occlusion: There was no significant difference in mean vection reponse between periphery occluded and non-occluded viewing conditions.

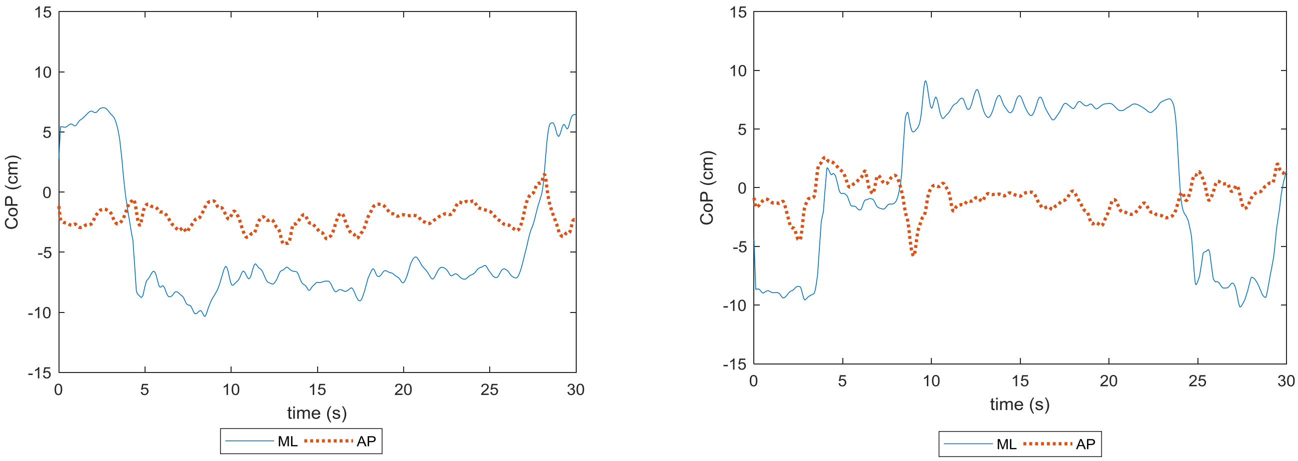
(ii) Interaction effects

There were no significant two-way or three-way interaction effects as shown in Table 4.

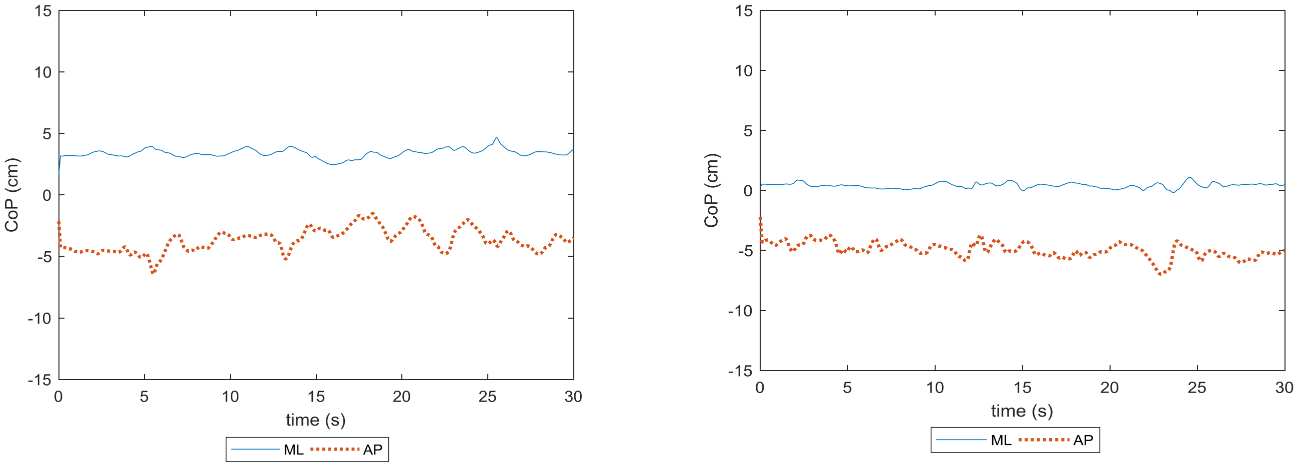
3.2.2. *Postural sway*

This section investigates possible relationships between vection strength and postural sway measured in Experiment 2. The CoP data depicting postural sway obtained from two participants while they observed the stimulus on two trials are shown in Fig. 11. The postural sway paths formed by tracing every point on the CoP waveforms are shown in Fig. 12. The convex polygons traversing the respective sway paths, from which the sway path areas were calculated, are shown in red. We used these sway path areas described in [26] as measures of the amount of participants' postural sway.

We used Pearson's coefficient to investigate the correlation between reported vection strength and corresponding postural sway represented by the area of their CoP paths. The correlation coefficients with p values indicating their respective significance levels for 12 trials (2 speeds × 3 frame rates × 2 peripheral occlusion conditions) for all participants are

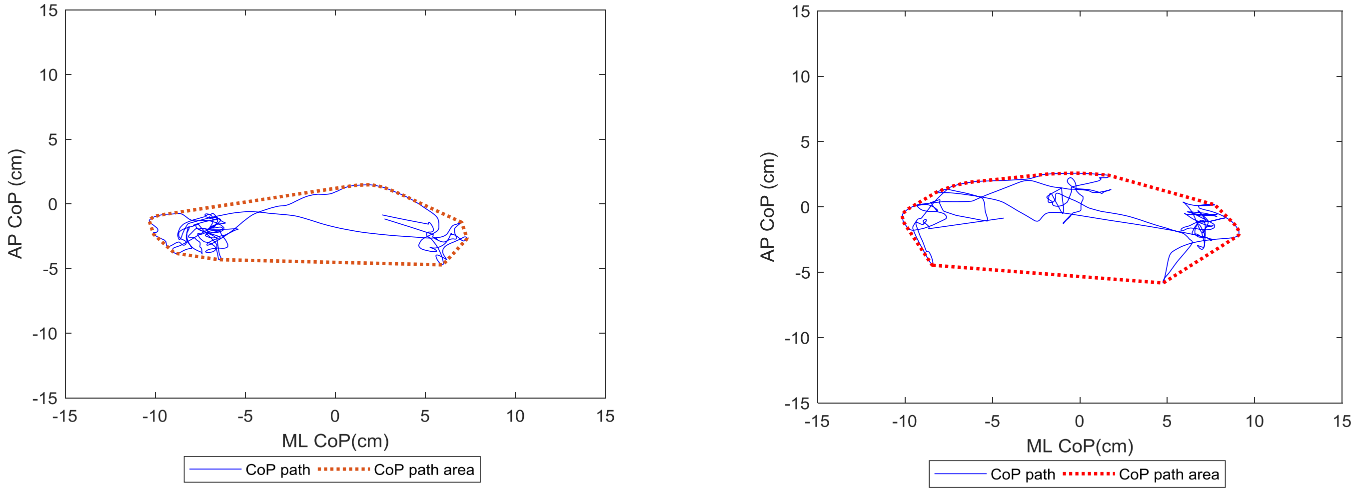


(a) Participant 6, 15-S-PNO **(b) Participant 6, 15-S-PO**



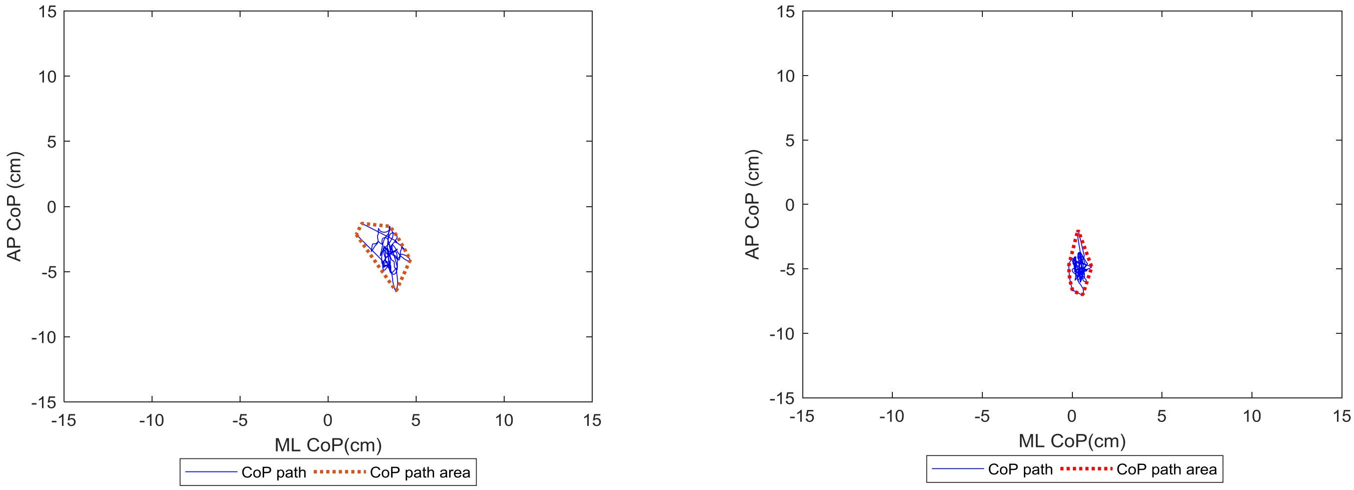
(c) Participant 8, 15-S-PNO **(d) Participant 8, 15-S-PO**

Fig. 11. Experiment 2 - CoP waveforms in the anterior-posterior (AP) and medial-lateral (ML) directions obtained from two participants (6 upper row, 8 lower row) while viewing the stimulus with periphery occluded (PO), (right column) and periphery not occluded (PNO), (left column).



(a) Participant 6, 15-S-PNO

(b) Participant 6, 15-S-PO



(c) Participant 8, 15-S-PNO

(d) Participant 8, 15-S-PO

Fig. 12. Experiment 2- paths traced from CoP data points in Fig. 11 (blue lines) and their corresponding bounding convex polygons (shown in red). (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

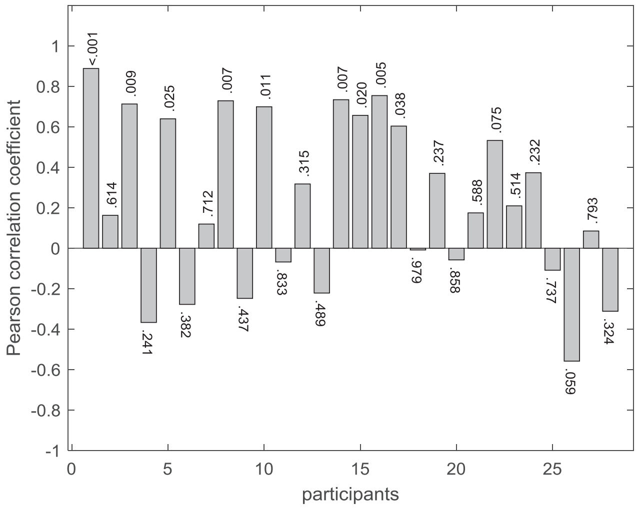


Fig. 13. Experiment 2 - Pearson's coefficient of correlation with p values between participants' perceived vection strength and level of postural activity.

shown in Fig. 13. Positive correlation values reflect an increase in postural instability (or postural sway) as perceived vection scores increase. Negative correlation coefficient values mean postural sway decreases as perceived vection increases. The lower the p value, the greater the likelihood (or significance) of a correlation existing between perceived vection and postural sway. As shown in Fig. 13, bars for 18 (64%) participants show positive correlations between perceived vection strength and postural sway, with 9 (50%) of them being significant ($p < .05$).

To combine the vection-postural sway correlation coefficients across observers, we followed the approach of [27] and converted them into a standard normal metric (using Fisher's r-to-Z transformation), computed the mean and confidence interval (CI), and then converted these back to correlations. A significant positive correlation ($r = 0.29$, 95% CI [0.174, 0.399], $p < .001$) was found between vection and postural sway.

3.2.3. Effects of stereoscopic movie parameters and peripheral occlusion on postural sway

A three-way rANOVA test was used to investigate the effects of movie parameters and peripheral occlusion on postural sway. In order

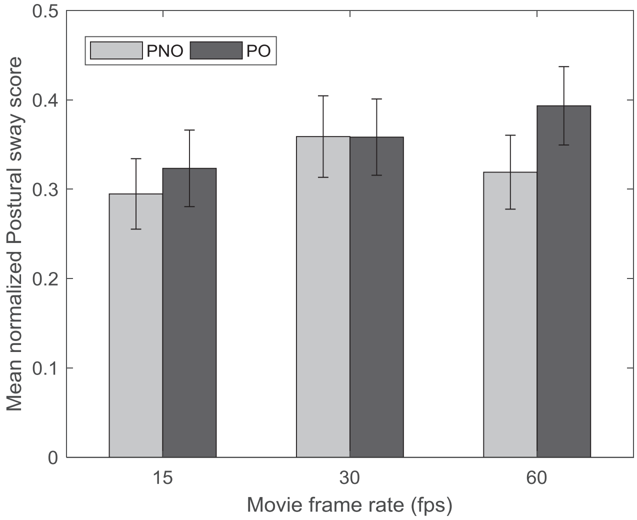


Fig. 14. Experiment 2 - effects of movie frame rate on participants' mean normalized postural sway for periphery not occluded (PNO), (grey bars) and periphery occluded (PO), (black bars). Data are collapsed across camera motion speed. Error bars represent ±1 standard error of the mean.

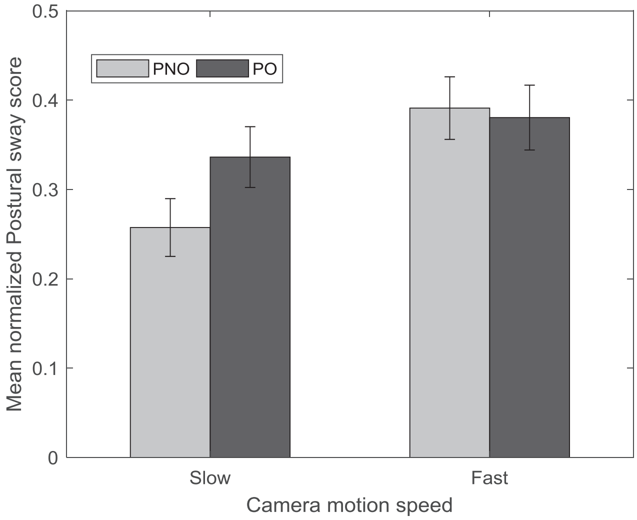


Fig. 15. Experiment 2 - effects of camera motion speed on participants' mean normalized postural sway for periphery not-occluded (PNO), (grey bars) and periphery occluded (PO), (black bars). Data are collapsed across frame rate. Error bars represent ±1 standard error of the mean.

Table 6
Experiment 2 - repeated measures analysis of variance for normalized postural sway. Results of the rANOVA analysis showing degrees of freedom (df), F-statistic, and p values, and effects size (partial Eta^2) for each stimulus parameter and their interactions.

Parameter	df (parameter)	df (error)	F	p	η^2
Movie frame rate	2	54	0.99	.377	0.053
Camera motion speed	1	27	4.74	.038	0.176
Peripheral occlusion	1	27	0.48	.494	0.031
Movie frame rate & camera motion speed	2	54	0.40	.669	0.024
Movie frame rate & peripheral occlusion	2	54	0.49	.617	0.025
Camera motion speed & peripheral occlusion	1	27	3.25	.083	0.051
Movie frame rate & camera motion speed & peripheral occlusion	2	54	0.36	.700	0.019

to compare the postural sway data from all participants on a uniform scale and account for differences in individual postures possibly influencing postural sway (similar to [28]), the convex areas of the CoP paths for each participant were normalized by the formula

$$a = (A_x - A_{min})/(A_{max} - A_{min}) \tag{2}$$

where

a = normalized postural sway score with range $0 \leq a \leq 1$
A_x = the path area of a single CoP observation
A_{min}, A_{max} = participant's respective minimum and maximum CoP path areas from all 12 observations.

The bar graphs in Figs. 14 and 15 show the effects of frame rate and speed on the average postural sway of participants for two viewing conditions. It appeared that there was an increase in the mean normalized postural sway score with increasing frame rate for the periphery-occluded conditions. There was also an apparent increase in mean normalized postural sway score with speed for both periphery-occluded and not-occluded viewing conditions. The results of the three-way rANOVA test to assess the main effects of and interactions between movie parameters and peripheral occlusion on participants' postural sway is presented in Table 6.

(i) Main effects

Movie frame rate: Results from the 3-way rANOVA presented in Table 6 suggest that there was no significant main effect of movie frame rate on participants' normalized postural sway.

Camera motion speed: Results in Table 6 show that camera motion speed had a significant effect on normalized postural sway. Fast-motion speed stimuli induced significantly greater postural sway than slow-motion speed stimuli (mean normalized postural sway = 0.297) as suggested by the bar graph of Fig. 15.

Peripheral occlusion: Table 6 shows a non-significant effect of peripheral occlusion on participants' normalized postural sway.

(ii) Interaction effects

As shown in Table 6, there were no significant effects of interactions between stimulus parameters on participants' normalized postural sway.

4. Discussion and conclusion

In these experiments we investigated (1) how participants' perceived self-motion varied with movie frame rate, simulated virtual camera speed and motion blur produced by the virtual camera's exposure, while viewing depictions of movement through a realistic virtual environment, and (2) how their postural sway covaried with levels of perceived self-motion and with the S3D movie parameters. Results from both experiments showed that the simulated motion speed had the strongest effect on vection, i.e. on average, faster motion speed produced more vection than the slower motion speed. This finding is consistent with previous studies that have shown a positive correlation between vection strength and stimulus speed [29,30]. There was also an effect of frame rate on vection, with the highest frame rate of 60 fps producing significantly higher vection than the lowest frame rate of 15 fps. This finding is consistent with [9] where vection strength was found to increase with motion smoothness due to higher frame rates. Motion blur had no significant main effect on vection, although conditions with no motion blur appeared to have stronger effects on vection at 60 fps than at lower frame rates.

Peripheral occlusion (PO) in Experiment 2 did not have a significant effect on vection. This is likely due to the fact that the 3D glasses already eliminate many extraneous visual surround cues that indicate the observer is not moving. The lack of an effect of the occluded periphery indicates that the remaining peripheral visual cues were not salient and thus did not significantly interfere with vection.

In our study, measures of postural sway in 18 of 28 participants correlated positively with vection; this correlation reached significance in 9 of the 18. Interestingly, the remaining 10 observers showed non-significant negative correlations between postural sway and vection strength. It appears that these participants adopted a rigid stance to stabilize themselves when experiencing vection. The average postural sway also correlated positively and significantly with average vection ratings.

There has been growing interest in the physiological consequences of vection, the most profound of which is Visually Induced Motion Sickness (VIMS) for recent review see [31]. Some researchers consider vection to either be a main contributor to, or to jointly occur with VIMS [32–34] and Nooij et al. [35] concluded that vection gain was the main contributor (amongst eye and head movement factors) to VIMS triggered by yaw rotation. On the other hand, several researchers in [5,36,37] have suggested that vection could play functional roles in controlling self-motion, navigation and spatial orientation, thus affirming the strong positive impact of vection on viewer enjoyment and immersion of S3D content. Given the potential for both positive and negative consequences of vection, self-motion percepts should be of primary concern to producers of high frame rate S3D content. Moving content should be tested for such negative consequences as VIMS, and ways to reduce the effect on vection and the resulting VIMS should be employed. One possible way of reducing vection in high frame rate S3D content would be to introduce some motion blur. However, in general, we found no, or weak, effects of motion blur on vection. One exception was a drop in vection strength between unblurred and motion blurred stimuli at 60 fps. This suggests that adding even a small amount of motion blur may be effective in reducing vection and VIMS in high- but not low-frame rate stimuli. Such a suggestion needs follow-up at other frame rates and speeds as this difference was found only at 60 fps, and in general there was no relation between motion blur and vection. Because humans fixate more at image regions with sharp (high frequency) edges [38] and less on regions with blurred edges, S3D content with sharper edges could result in better immersion and spatial presence than content with blurred edges. Illusions of self-motion have been shown to be directly related to spatial presence [21], and therefore an increased spatial presence arising from observing such content potentially leads to greater chances of vection (and VIMS) occurring.

There has been considerable interest in finding ‘objective’ measures of vection [5,39,40]. While it might seem strange to look for objective measures of an inherently subjective experience, several papers have argued for the utility of such measures. For example, Palmisano et al. [5] have argued that such measures are necessary for confirmatory evidence when vection displays are weak or when one wishes to study cognitive influences on vection. Vection is an indicator of a behaviourally important parameter, one’s self motion, and it is not surprising that vection correlates with other behavioural responses to self-motion. Measuring correlates of vection is useful for determining if behavioural responses to the same stimulus covary and might indicate evidence for common neurophysiological substrates (e.g. [41–44]). However, postural responses and vection can be incongruent in direction and timing [45] which argues against a simple causal relationship. As an ‘objective’ indicator of vection, sway could serve as confirmatory data for subjective reports. We did find a relation between self-reports of vection and sway measures consistent with earlier reports. However, we found a significant individual correlation between vection and sway in only 9 observers and some observers had (weak) negative rather than positive correlations. Similarly, equivalent statistical analysis of the effects of frame rate, speed and exposure on sway parameters produced results generally consistent with similar analysis for subjective vection responses but not identical and differing in the significance of key effects. While differences in the sensitivity of the measures and statistical uncertainty could underlie these differences in outcomes, the results suggest some caution in the use of sway as direct proxy for vection. The relation is likely non-linear and stimulus dependent at best. Note that several studies have suggested that spontaneous sway with eyes closed can predict the degree that a subject will experience vection when exposed to optic flow stimuli (e.g., [46–48]). While this indicates a link between postural stability and *susceptibility* to visual motion it does not necessarily predict a strong correlation between vection and online postural variation while viewing a self-motion display.

As noted above, while too much vection may result in discomfort, for many viewers the experience of some vection is an important determinant of immersion. To ensure that viewers have an optimal experience, it is important that content creators understand the parameters that impact this ‘sweet-spot’. Our results suggest that the increased motion fidelity due to increasing frame rate produces more effective vection stimuli with little impact of motion blur. Frame rate effects need to be considered in conjunction with image size, simulated speed, direction and other known determinants of vection to predict the ultimate effect of the image sequence on vection and VIMS. As industry moves to ever higher frame rates in simulation and VR, future work will need to assess whether vection continues to increase with frame rate or if it saturates.

Conflict of interest

The authors declared that there is no conflict of interest.

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Appendix A. Supplementary material

Supplementary data to this article can be found online at https://doi.org/10.1016/j.displa.2019.03.002.

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