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Measuring circular vection speed in a virtual reality headset☆

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ABSTRACT

Understanding the relationship between vection speed and display speed is important to help ensure accurate self-motion experiences in a variety of applications. In the present research, a virtual optokinetic drum was used to induce circular vection at three distinct constant velocities and a method for measuring circular vection speed was developed and examined. In Experiment 1, vection strength was measured using a traditional magnitude estimation rating technique. An optokinetic drum presented on a virtual reality (VR) headset rotated in the yaw axis at slow, medium, and fast speeds. Magnitude estimation ratings were greatest during the fast condition in Experiment 1, replicating previous findings and validating the use of the virtual optokinetic drum in a VR headset. In Experiment 2, participants spun a circular knob in a clockwise or counter-clockwise direction to index their vection speed, direction and duration. The speed at which participants spun the knob increased with drum speed. Vection speed was much faster than the optokinetic drum's speed, demonstrating that participants may perceive self-motion at faster speeds than intended. It is recommended that indices of vection speed such as the circular knob be used to better understand the relationship between graphic speed and vection speed.

1. Introduction

Vection generally refers to the visual illusion of perceived self-motion in a stationary observer. Vection is influenced by the optic flow trajectory [1]. Elements in a visual scene that move in a common direction may produce a pattern of optic flow that results in perceived motion in the opposite direction [2,3]. For example, movement of elements that expand radially from the center of a display can produce vection in the forward direction. This has been described as linear vection [4] or vection in depth [5], and is an illusion that is commonly experienced in day-to-day life. For instance, when a driver is stopped at a red light, an adjacent vehicle that begins moving forward can create an optic flow pattern in the driver's peripheral field in the forward direction. This can create an illusion that the driver is rolling backward. The driver may frantically increase pressure on the brake pedal only to realize that their vehicle was not moving. The present research is focused on another type of illusory self-motion: circular vection. Circular vection occurs when stimuli in the visual scene appear to rotate about the yaw axis, causing the observer to experience spinning in the opposite direction. The objective of the present research was to examine how circular vection is affected by the speed at which stimuli are rotated around the observer and to examine the relationship between perceived vection strength and perceived vection speed.

1.1. Vection measurement

Some researchers have used postural sway [6–8] and eye movements generated when fixating elements in the visual field called optokinetic nystagmus to measure vection [9,10]. However, it is not yet established how effectively these methods index vection. In contrast, there is a large literature focused on measuring self-report of the strength at which an observer experiences vection. Studies have investigated how vection strength is affected by the visual angle of the stimulus [11–13], different optic flow trajectories [1,14–17], background-foreground relationships in a visual scene and stimulus eccentricities [18–20], binocular depth cues [21,22] and more.

Vection strength has been measured using magnitude estimation (ME) ratings [23–26]. ME ratings typically require the participant to monitor their experience of vection when observing a reference stimulus. Participants are instructed to assign that reference stimulus a value in the middle of the scale (e.g., 50 on a 100-point scale). Participants rate all subsequent trials relative to their experience on the modulus trial.

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Therefore, if participants experience vection that is twice as strong as vection in the modulus trial, they would rate it a '100' on a 0–100 scale. ME provides a range of values that allows researchers to identify difference in vection experience based on a common reference value. ME also allows measurement of perception in different sensory systems (i.e., judging audibility of auditory cues) making it a versatile psychophysical measure [27]. However, a limitation of ME is that it relies on memory of the modulus display because it requires comparing vection experienced on a given trial to vection experienced during a modulus trial at the beginning of the experiment [28–30]. Another limitation of ME is that vection strength is a hypothetical construct that is interpreted by the participant and translated onto an arbitrary rating scale. This can make ME data difficult to interpret and compare across participants [31]. Likert scales have also been used extensively to measure vection strength [8,32,33]. Likert scales also present some concerns regarding reliance on memory to make judgements. Moreover, Likert scales may present more ambiguity in score interpretation across participants than ME ratings as there is no common reference value.

Other measures that have been used to index vection include vection onset time (i.e., the amount of time from the beginning of a trial it takes to experience vection) [34–36], vection duration (i.e., how long vection lasts) [17,35,36], perceived distances traversed as a result of experiencing vection [2,3], using a joystick to indicate presence of vection and its direction [37], and discrimination tasks where participants reported when they experience vection [38].

Some studies have used verbal measures of linear speed estimations of vection in experiments where participants are travelling in a road vehicle [39], or road vehicle simulator [39,40]. A circular vection study by Melcher and Henn had participants rotate a circular knob while in an optokinetic drum. It was found that knob velocities were approximately similar to the velocities of the drum [41]. Palmisano and Gillam used a nulling technique in which participants were able to rotate the chair in the same direction as the spinning optokinetic drum [20]. As the speed of the drum increased, participants increased the chair speed to null their sense of vection. In sum, studies have used measures of speed to examine vection and found that the experience of vection is affected by the speed of the stimulus.

There is important practical value in judging vection speed. One such example is in vehicle simulation, where whole-body self-motion perception is required because visual and other sensory systems must perceive coherent self-motion information to produce compelling self-motion experience and to mitigate simulator sickness [42–49]. Research by Bos, van den Berg-Kroon, Houben, and Kuiper, and Owens, Gu, and McNally, examined linear self-motion speed in a real and simulated land vehicle [39,40]. Melcher and Henn, and Palmisano and Gillam examined vection speed when in an optokinetic drum [20,41]. The current study builds on research by these authors by using a circular knob to index vection speed in a virtual optokinetic drum presented on a virtual reality (VR) headset for the first time.

1.2. Present research

The objective of the present research was to measure circular vection speed and to determine how it is affected by the speed at which stimuli are rotated around an observer. Further, the relationship between perceived vection strength and perceived vection speed were examined by comparing results from the two experiments described in this paper. Two experiments are reported in which circular vection was induced by presenting a virtual optokinetic drum on a VR headset. The speed at which the virtual drum appeared to rotate around the observer was varied in both experiments. In Experiment 1 (E1), the use of the virtual optokinetic drum in a VR headset was validated by obtaining ME ratings of vection strength and comparing these ratings to those found throughout the literature. In Experiment 2 (E2), a rotating knob apparatus was used to index participants' experience of vection speed, as well as vection direction and duration. An expected advantage of the rotating knob apparatus over ME ratings was that the rotating knob apparatus would provide specific measurement units of vection speed (i.e., °/s, m/s) while participants experience vection. Moreover, vection speeds can easily be compared across participants. In contrast to ME ratings, the rotating knob technique is not reliant on memory of a previous modulus trial.

1.3. Experiment 1: Magnitude estimation ratings of circular vection in a VR headset

E1 was conducted to validate the use of a virtual optokinetic drum to induce circular vection in a VR headset. In E1, a virtual rendition of a physical optokinetic drum was presented on a VR headset, resembling previously used stimuli [8,50,51]. The virtual drum had alternating vertical black and white stripes that were rotated at three distinct constant speeds. These stripes moved clockwise (CW) or counter-clockwise (CCW). Vection strength, direction and duration were measured. Vection strength was measured using a ME rating scale and vection duration was also measured in seconds. It was hypothesized that increasing drum speed would produce greater ME ratings and longer vection durations. Results indicating stronger vection would be consistent with the known positive relationship between perceived display speed and vection strength [4,26] (see Tamada and Seno for a review [52]) and validate the use of the VR optokinetic drum to produce reliable vection for the purpose of our research.

1.4. Method

1.4.1. Participants

A total of 18 undergraduate university students were recruited in exchange for course credit ($M_{AGE} = 22.7$, $SD_{AGE} = 5.7$). The experimental protocol was approved by a university ethics board. Two participants did not complete the experiment because they experienced slight nausea, leaving 16 participants (6 female, 10 male) in the final analysis. All participants reported seeing the display clearly and none had a history of vestibular disorders.

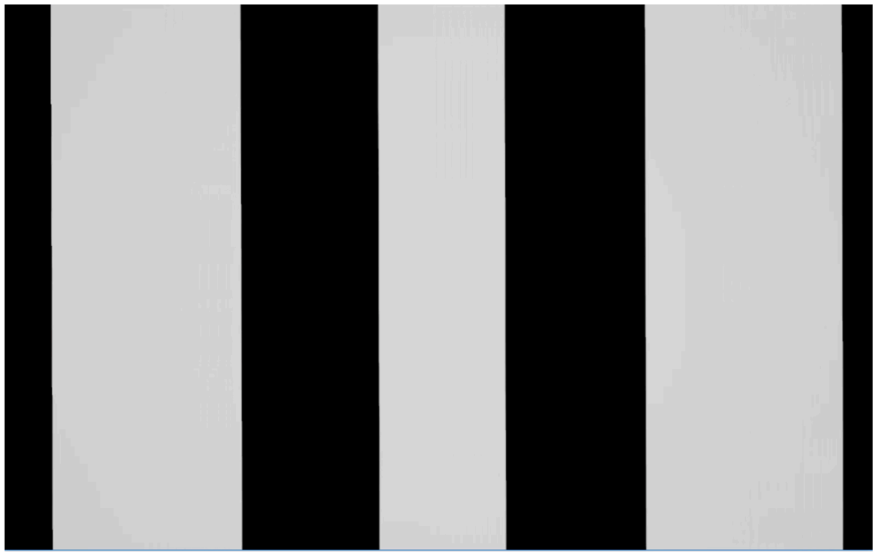
1.4.2. Design

The experiment was a 3 (Drum Speed: 'slow' − 37.5 °/s vs. 'medium' − 56.25 °/s vs. 'fast' − 75 °/s) by 2 (Direction: CW vs. CCW) repeated-measures design. The six conditions were presented six times each, totaling 36 trials that were presented in random order to each participant. The 36 experimental trials were split across four blocks (9 randomized trials per block). Each trial lasted 30 s. During a trial, the display moved at one of the six pre-selected speeds. Each block lasted approximately 5 min and was followed by a 5-minute break to avoid cybersickness resulting from prolonged VR headset use. The experiment lasted approximately one hour.

1.4.3. Apparatus

VR headset. An Oculus Rift DK2 VR headset provided a 110° diagonal visual angle, a native resolution of 960 × 1080 pixels per eye, and a 75 Hz refresh rate. The left and right eye displays presented the same image at different perspectives permitting 3D perception of the stimuli. The inter-ocular distance (IOD) of the VR headset was set at 64 mm for all participants. To ensure that the virtual drum was perceived as the interior of a cylinder, participants were asked if the stimulus appeared convex, concave, or flat at the start of the experiment. All participants reported that it appeared concave.

XBOX© 360 Gamepad. A USB-integrated gamepad was used to record vection ratings and durations and is presented in Fig. 1. Participants selected a value on a scale that represented the strength of experienced vection. This was done using the 'Y' button to navigate up on the scale and the 'A' button to navigate down on the scale. Participants could increase or decrease their rating on the scale by increments of '5' by moving up and down the scale. The 'B' button was used by the a)



b)

Fig. 1. a) Optokinetic drum displayed on 2D monitor. Stripes in the above image appear to vary in size as a result of the 3D curvature of the drum when seen in the VR headset. b) Gamepad used to navigate ME rating scale after each trial in E1 (image adapted from New Game Network, 2013).

participant to finalize the selection of their rating before moving on to the next trial. Participants pressed and held the top-right shoulder button when they experienced vection which indexed vection duration.

1.4.4. *Stimuli*

A computer with an Intel Core I-7 processor, an NVIDIA GeForce GTX980 graphics card and 16 GB RAM was used to run the experiment. The graphical display representing the optokinetic drum was built in Unreal Engine 4.8. The graphics display presented in the VR headset simulated a drum with a 200-cm diameter. When wearing the VR headset, the observer's viewpoint was at the center of the virtual drum 100 cm away from the surface of the drum. Each stripe in the display corresponded to a width of 33 cm in the virtual graphics environment, and subtended a horizontal visual angle of 10.85° at a virtual viewing distance of 100 cm. The vertical stripe pattern that was presented on the VR display moved in the CW or CCW directions at three speeds: 37.5°/s ('slow'), 56.25°/s ('medium') and 75°/s ('fast'). This resulted in six conditions. These three speeds were selected after informal pilot testing of various candidate speeds on the two experimenters involved in the study and several lab mates. The objective was to identify three speeds that showed a distinct difference in perceived vection speed in relation to one another. The three speeds were selected based on consensus among participants.

1.4.5. *Procedure*

Participants were seated upright on a chair in a dark room with their feet touching the ground and their heads supported by a pillow against a wall while they looked straight ahead and kept their head still. Once participants were comfortably seated, the display was adjusted in the VR headset to appear in front of the participant. The display was configured so that participants were positioned in the center of the virtual optokinetic drum. The VR headset display was mirrored on a monitor for the experimenter.

Participants completed 3–5 practice trials to become familiarized with the VR headset, stimulus, task and use of the gamepad. Participants asked the experimenter any questions they had. Following the practice trials, the experiment began. The experiment began with a modulus display. This was a 40 s display of the stripes moving at the medium speed in the CW direction for 20 s and in the CCW direction for 20 s. Participants were instructed to monitor their experience of vection when observing the modulus display and to assign their vection experience on the modulus a value of '50′ on a visually presented 0–100 scale. In accord with general ME rating protocol, the value and associated vection strength experienced during the modulus display was used as a reference by the participant to rate all subsequent trials. Participants rated vection strength at the end of each trial when the 0–100 rating scale appeared. An index of vection duration was also obtained by having participants hold the right trigger of the gamepad from the moment circular vection was experienced until it was no longer experienced. Trial sequence during the experiment is illustrated in Fig. 2.

1.5. Results

Vection strength from the ME rating scale and vection duration from right trigger pulls were analyzed in two separate 3 (Drum Speed: Slow vs. Med vs. Fast) by 2 (Direction: CW vs. CCW) repeated measures ANOVAs. Post-hoc comparisons were made using 95% confidence intervals described by Jarmasz and Hollands [53].

1.5.1. Vection strength

The ME ratings of vection strength for each drum speed (e.g., slow, medium, and fast) are shown in Fig. 3. As predicted, there was a significant main effect of Drum Speed, $F(2, 30) = 25.04$, $p < 0.001$, $R^2 = 0.63$, where faster drum speeds resulted in greater ratings of vection strength. The 95% confidence intervals indicated a significant difference in perceived vection strength between all speeds in both the CW and CCW directions. As shown in Fig. 3, vection strength did not differ between CW and CCW conditions ($F < 1$), and there was no interaction between Drum Speed and Direction ($F < 1$).

1.5.2. Vection duration

Vection duration was the cumulative amount of time that participants experienced vection in a trial. This was represented by participants pulling the right shoulder button of the gamepad when they experienced vection. Vection durations did not differ as a function of Drum Speed or Direction and there was no interaction between these factors (all F's $<$ 1).

To summarize E1, vection strength was measured using ME ratings, which is a commonly used technique. As reported in studies using a physical optokinetic drum, increasing the rotation speed of the virtual drum resulted in participants reporting greater vection strength, replicating findings of studies that have used a physical optokinetic drum [4,52,54] and validating the use of a VR headset optokinetic drum in the present study.

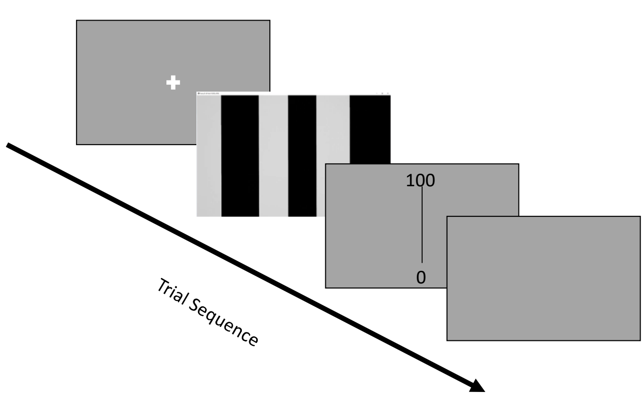


Fig. 2. Sequence of a trial in E1. From left to right: participants saw the fixation cross, followed by the virtual drum moving in the CW or CCW direction at one of the three predetermined speeds. The rating scale then appeared at which point participants used the gamepad to rate their vection. The trial ended with the appearance of a grey screen.

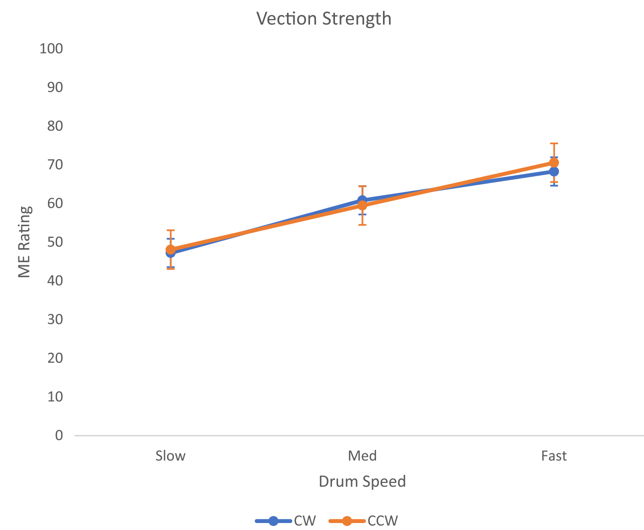


Fig. 3. ME ratings of vection strength for the three drum speeds in the CW and CCW directions. Error bars represent 95% confidence intervals for the analysis.

1.6. Experiment 2: measuring circular vection speed using the rotating knob

Research by Bos et al., and Owens and colleagues examined perceived self-motion speed [39,40]. In Bos and colleagues' experiment, participants verbally reported linear self-motion speeds when in a vehicle on a track. Researchers did not find statistically significant differences across estimated versus actual self-motion speeds across conditions. However, they found that on average, participants underestimated their speed by 5 km/h.

Owens et al., investigated linear self-motion speed perception in a driving simulator [40]. They manipulated speed and contrast of the visual stimulus presented on a monitor by using computer generated fog overlaid on the footage from the actual scene. They found that speed perception differed by varying the visual stimulus speeds. However, they did not report comparisons of actual versus estimated speeds, though means indicated that participants estimated speeds that were close to actual speeds.

Research conducted by Bos and colleagues, and Owens and colleagues examined the relationship between perceived self-motion speed and virtual display speed [39,40]. The present experiment built on their work by investigating the relationship between display speed, vection speed and vection strength in a VR optokinetic drum presented in a VR headset. This was done by using a circular knob to continuously report vection throughout a trial in Experiment 2 (E2). The primary objective of E2 was to understand how manipulation of drum speed can impact vection speed. The second objective of E2 was to understand the relationship between vection strength and vection speed by comparing vection speed reports obtained in E2 to vection strength reports obtained in E1.

In E2, a circular knob was developed to measure circular vection speed. The knob was held by participants and could be rotated CW or CCW at the speed at which they experienced vection while they attended to the virtual optokinetic drum display in the VR headset in real-time. The stimuli speeds and conditions presented in the VR headset in E2 (e.g., slow, medium, fast speeds) were identical to those in E1. When participants experienced vection, they were to rotate the knob in the opposite direction and at the speed of their perceived self-motion. The knob apparatus recorded vection speed, direction, and duration in each trial. It was hypothesized that faster drum speeds would induce faster vection which would be reflected in faster knob rotations.

1.7. Method

1.7.1. Participants

A total of 16 participants (4 female, 12 male) were tested (M_{AGE} = 19.0, SD_{AGE} = 1.8). These were different participants than those that completed E1. Fourteen participants were undergraduate students that received course credit in return for their participation. Two participants were experimenters involved with the study. Two participants did not experience vection and were therefore excluded from the analysis. Fourteen participants were included in the final analysis. All participants had normal or corrected-to-normal vision and no history of vestibular problems. Two participants were left-handed.

1.7.2. Stimuli, design and apparatus

The stimuli, design, computer, and VR headset used in E2 were identical to those used in E1. A Spintrak rotary knob was used to index speed of circular vection and is presented in Fig. 4. The knob was circular, had a 4.4 cm diameter and could be turned either CW or CCW continuously. The knob had a tachometer and a high-resolution pulse rate of 1200 units over 360° for precise knob position tracking and recording. The knob was USB-integrated with custom software that logged turn rates in °/s at 75 Hz. It was housed in a custom-built wooden box and rested on the participant's lap during testing.

1.7.3. Procedure

A summary of the trial sequence is presented in Fig. 5. As in E1, participants were seated upright in the dark and viewed the virtual drum on the VR headset in E2. There were four 9-trial blocks with each block separated by 5-min breaks. The 9 trials in each block were randomized. Participants were instructed to turn the knob in the opposite direction and at the same speed as their perceived vection within each trial. They turned the knob with the index finger of their dominant hand and held the knob on their lap with their other hand. If participants did not experience vection, they were instructed not to turn the knob. For each trial, vection duration was indexed as the cumulative time (in s) the knob was rotating.

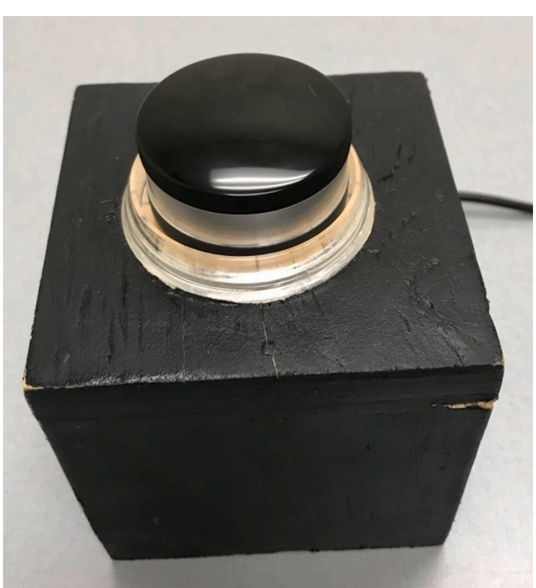


Fig. 4. Knob controller used to measure vection speed.

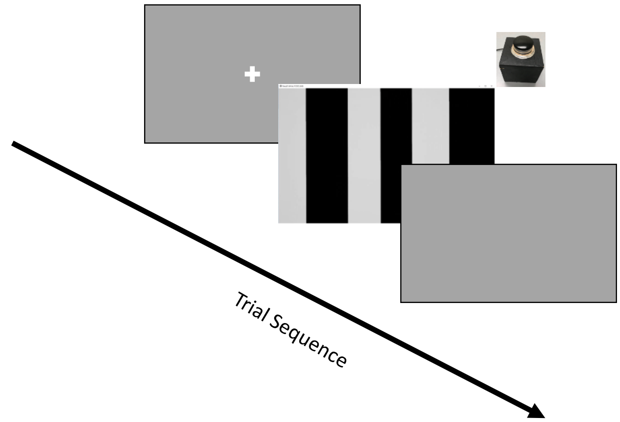


Fig. 5. Sequence of a trial in E2. From left to right: participants saw the fixation cross, followed by the virtual drum rotating. As they attended to the stimulus, they used the knob to indicate their vection. A grey screen appeared when the trial ended.

1.8. Results

Vection speed and duration were analyzed in two separate 3 (Drum Speed: 37.5 °/s vs. 56.25 °/s vs. 75 °/s) by 2 (Direction: CW vs. CCW) repeated measures ANOVAs. Post-hoc comparisons were made using 95% confidence intervals [53].

1.8.1. Vection speed

Vection speed was represented as the rate at which participants rotated the knob. There was a significant main effect of Drum Speed on knob rotation, $F(2, 26) = 29.64$, $p < 0.001$, $R^2 = 0.70$. As shown in Fig. 6, participants turned the knob faster as the virtual drum speed was increased. The 95% confidence intervals indicated differences between all speeds in the CW direction, and between the slow-fast and medium-fast speeds in the CCW direction. There was no main effect of Direction and no interaction between Drum Speed and Direction (F's < 1) on knob rotation.

1.8.2. Vection duration

Vection durations were the cumulative instances within a trial that the knob rotated in seconds. There was a significant main effect of Drum Speed on vection duration, $F(2, 26) = 13.98$, $p < 0.001$, $R^2 = 0.52$. Vection duration generally increased with Drum Speed. No other effects were significant. The 95% confidence intervals indicated differences between slow-medium and slow-fast durations in the CW direction, and

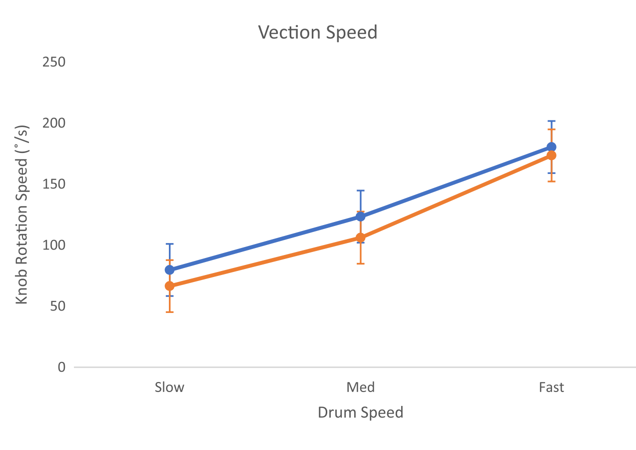


Fig. 6. Knob Rotation Speed (°/s) for drum speeds in the CW and CCW directions. Error bars represent 95% confidence interval for the analysis.

between the slow-fast durations in the CCW direction. There was no main effect of Direction and no interaction between Duration and Direction (F's < 1).

1.8.3. Comparing drum speed, vection speed, and vection strength

The objective of E2 was to examine whether the experience of circular vection speed is affected by the speed at which a visual stimulus is rotated around the yaw axis when using a VR headset. Participants' experience of vection speed was measured using a circular knob in E2: participants turned the knob to match their perceived speed of vection. The results showed that vection speed increased as the rotation speed of the virtual drum increased for CW and CCW rotations of the virtual drum.

These results raise the following questions: 1) What is the relationship between vection strength obtained in E1 and vection speed obtained in E2? 2) Is there a difference between drum speed and vection speed values? 3) Can drum speed predict vection speed? Question one was addressed by performing a Pearson correlation between vection strength and vection speed. It was hypothesized that vection strength and vection speed would be positively correlated. Question two was addressed by performing single sample t-tests between each drum speed and corresponding vection speed to determine if they were different. It was hypothesized that vection speed and drum speed would be different. Question three was addressed by performing a simple linear regression where drum speed was a predictor of vection speed. Taken together, answering these three questions provides a deeper understanding of the relationship between vection strength, vection speed and display speed.

Correlation between vection strength and vection speed. A Pearson correlation compared ME ratings of vection strength from E1 to vection speed scores obtained using the circular knob in E2. CW and CCW conditions were collapsed for slow, medium and fast drum speed conditions. A hypothesis test of the significance of the Pearson correlation coefficient (2-tailed) was performed to obtain the p-value. The correlation between vection strength and speed was positive, as predicted but the correlation coefficient was not significant, $r(40) = 0.22$, $p > 0.05$.

Single sample t-tests between drum speed and vection speed. The objective of these analyses was to determine if there is a significant difference between drum speed and vection speed. A single sample *t*-test was performed for each drum speed condition (e.g., 37. 5 compared with vection speed for slow drum speed condition; 56.25 compared with vection speed for medium drum condition, etc…) resulting in three different single sample t-tests. Effect size was calculated for each *t*-test using the ***r*** statistic [55]. In each *t*-test, the drum speed was used as the 'test value' (e.g., 37.5, 56.25, or 75) and compared to vection speed responses for the slow, medium and fast conditions separately. The *t*-test for the slow condition was significant $t(29) = 2.38$, $p < 0.05$, $r = 0.40$. The *t*-test for the medium condition was significant, $t(29) = 2.99$, $p < 0.01$, $r = 0.49$. The *t*-test for the fast condition was significant, $t(29) = 3.84$, $p < 0.01$, $r = 0.58$. In all conditions, vection speeds were significantly greater than drum speeds and had moderate effect sizes for the slow and medium t-tests, and a large effect size for the fast *t*-test.

Simple linear regression predicting vection speed from drum speed. Findings from the single sample t-tests above suggest that participants experience faster vection than the speed of the drum. The equation from the simple linear regression predicting the relationship between vection and drum speed is as follows: $\textit{vection speed} = -40.29 + 2.91X$ where X represents a 1-unit change in drum speed. Therefore, for every 1 °/s change in displayed drum speed, there is a 2.91 °/s change in vection speed as indexed with the potentiometer knob method controlled by participants. The linear regression was significant, $F(1,39) = 17.08$, $p < 0.001$, $R^2 = 0.305$. Thus, 30.5% of the variance in vection speed can be explained by changes in drum speed. The correlation from the regression analysis between drum speed and vection speed was also significant, $r(1, 39) = 0.552$, $p < 0.01$, one-tailed.

2. General discussion

Findings from the current paper have validated the use of the optokinetic drum to induce vection in a VR headset and established the rotating knob as a method to produce circular vection speed measures. A Pearson correlation examining the relationship between vection strength and vection speed was not significant despite being positively correlated. This finding indicates that the relationship between vection speed and strength may be more complex than anticipated.

Like previous studies, the current study indicated faster vection associated with faster display speeds [20,39–41]. However, these other studies investigating vection speed found that perceived self-motion speed did not differ substantially from display speed. Palmisano and Gillam as well as Melcher and Henn found that physical drum speeds were similar to reported vection speeds [20,41]. Bos et al., and Owens et al., found that participants estimated linear self-motion speeds approximated graphic speeds [39,40]. This differs from findings from the current study where vection speeds were significantly different than drum speeds as revealed by the single sample t-tests in Section 3.2.3. Results showed that vection speeds were much faster than drum speeds. However, the current experiment differs substantially from these other studies in many ways. For instance, the current study is the only one that examined circular vection with a virtual optokinetic drum in a VR headset. By contrast, Palmisano and Gillam, and Melcher and Henn used a physical optokinetic drum [20,41]. Bos et al.'s study as well as Owen and colleagues' study used linear self-motion stimuli of realistic patterns presented on various displays, in real vehicles or headset systems and had participants make verbal judgements of self-motion [39,40]. It may be the case that cues to vection speed may be different in a virtual optokinetic drum used in the present study than a physical optokinetic drum used by [41] and [20]. Additionally, the virtual optokinetic drum in a VR headset in the current study may provide less detail to self-motion speed than the realistic scenes viewed during linear self-motion used by [39] and [40], resulting in self-motion speed percepts that differ substantially than display speeds. In a nutshell, results from this study indicate that vection speed was substantially greater than display speed. In contrast, other studies have shown that participants estimation of speed is similar to display speed, but these studies used different stimuli and measures. Analyses here using a simple linear regression have allowed us to build a model to predict vection speed from drum speed. Further research should investigate relationships of display and vection speed and to validate and improve this model.

In recent years, neurophysiological studies have attempted to identify brain regions that become active during vection percepts [56,24,57,58]. For instance, Stróżak et al. found that anterior-frontal cortical regions showed reduced activity during vection compared to no vection conditions [58]. Kirollos et al. demonstrated that strong vection responses indexed by high ME ratings correlated with increased brain activity in the cingular sulcus visual area, in the parieto-insular vestibular cortex (PIVC), and adjacent posterior insular cortex [24]. Uesaki and Ashida also found increased PIVC activity during vection compared to no vection conditions among other cortical regions [58]. Kirollos et al.'s study used linear self-motion stimuli that signaled acceleration and therefore differs from the constant velocity circular vection display used in the present study. However, recent efforts on localizing brain regions associated with processing vection demonstrate the potential for using neuroimaging techniques as identifiers and measures of vection experience in future research.

3. Conclusions

The optokinetic drum is a classic apparatus that has been used to discover many characteristics of self-motion perception [11,14,20,59]. In E1, a VR display of a virtual rendition of the optokinetic drum was used to produce circular vection. Magnitude estimation ratings of vection strength increased as the speed at which the virtual optokinetic drum was spun, replicating previous findings [4,26,52]. The virtual drum was also used in E2 to induce vection. Instead of magnitude estimations ratings, a circular knob apparatus was implemented wherein participants spun the knob to match their perceived vection speed. The knob rotation data showed that perceived vection speed varied directly with changes in the rotation speed of the virtual drum.

Results from E2 provide a measure of vection that can be indexed using °/s, making this measure of vection easy to interpret and compare vection experience across participants. Further, results from E2 determined precise vection speeds for each drum speed used and findings indicate faster vection than drum speed. This link between display speed and vection speed has potentially important implications for applications such as vehicle simulation. Specifically, in motion-base flight and land vehicle simulators, multi-sensory cues from the visual display, motion bases, and audio system must be perceptually synced to enhance realism and reduce the possibility of simulator sickness arising from sensory mismatches in simulators [42–49]. Findings from the current study uncover the relationship between graphic display speed and perceived self-motion speed that can better help calibrate visual display speeds to auditory and vestibular cueing speeds in simulators. There may be similar implications for gaming where estimated locomotion speeds implemented by game developers may differ from vection speeds perceived by the gamer, inadvertently contributing to user error, discomfort or visually induced motion sickness in gamers. Instruments to measure vection speed analogous to the rotating knob apparatus used herein should be used and developed in linear vection speed research to ensure multisensory information in simulators is consistent to enhance realism in virtual environment applications.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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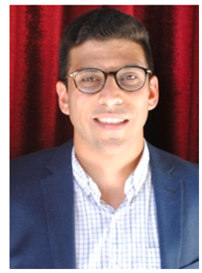

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