5-11-2023

Magnitude estimates of angular motion: Perception of speed and spatial orientation across visual and vestibular modalities

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Magnitude Estimates of Angular Motion:

Perception of Speed and Spatial Orientation Across Visual and Vestibular Modalities

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A dissertation submitted to the Graduate Faculty of

JAMES MADISON UNIVERSITY

In

Partial Fulfillment of the Requirements

For the degree of

Doctor of Audiology

Department of Communication Sciences and Disorders

May 2023

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Acknowledgments

This study would not have been possible without the direction and support of my dissertation committee chair and advisor, Erin Piker, Au.D., Ph.D., CCC-A. Her consistent guidance throughout all four years of my graduate education was instrumental in not only the completion of this study, but also in my love of research and the vestibular system. I would further like to thank my dissertation committee members, Carol Dudding, Ph.D., SLP-CCC and Lincoln Gray, Ph.D. Dr. Dudding's expertise in simulation training in graduate education was useful in navigating a novel virtual reality optokinetic stimulus. Dr. Gray's experience in psychoacoustics research helped guide our approach to vestibular psychophysics. Many thanks to all the members of my dissertation committee for their feedback and support.

I would also like to extend my sincere thanks to Daniel Romero, Au.D., Ph.D., CCC-A for his hard work in designing the study and creating the virtual reality stimulus using the Oculus Go. I began data collection for this project as a first-year graduate student with little research experience and am so grateful he took me under his wing in the vestibular lab. I also had the pleasure of working with Laura Fernan, who assisted with data collection.

I'd like to recognize the six other women in the JMU Audiology Class of 2023: Brenna, Sarah, Haley, Ellen, Michelle, and Lara. They provided me with a safe, supportive community during graduate school and all of its challenges.

Finally, I would like to thank Mom, Dad, Paulie, Eileen, Peter, and Gwyneth for cheering me on these last four years. Whether in person or over the phone, their words of encouragement always came right when I needed them.

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Abstract

Both the vestibular system and optokinetic system generate conjugate eye movements in response to either movement of the head or movement of the visual surround. Both systems help to maintain gaze stability. While the VOR is most sensitive to input frequencies above .2 Hz, the optokinetic system helps maintain gaze stability at lower frequencies. Previous research on perceptual thresholds across the two sensory modalities shows that there are frequency-dependent differences between vestibular and visual perception. The purpose of this study is to extend previous vestibular psychophysics work by 1) comparing magnitude estimates from vestibular stimulation to visual stimulation across multiple frequencies, and 2) assess the feasibility of using virtual reality to provide an optokinetic stimulus equal to that of the rotary chair at frequencies where both systems are sensitive.

Participants were exposed to 12 experimental conditions of angular rotation of varying frequencies and peak velocities across both sensory modalities. Vestibular stimulation was provided with a rotary chair and equivalent visual stimulation was provided with a virtual reality headset. Participants provided magnitude estimates of their speed and spatial orientation using a visual analog scale. Results reveal that speed magnitude estimates increased with peak velocity and frequency for both modalities. Spatial orientation magnitude estimates decreased with increasing frequency and increased with increasing peak velocity. Spatial orientation was underestimated under visual stimulation. Based on these results, it was concluded that at frequencies from 0.08 to 0.32 Hz, both vestibular and visual modalities provide adequate cues for motion sensitivity and virtual reality can be used as an OKN stimulus to assess motion perception (specifically speed/intensity).

I. Introduction

A. Vestibular System

The vestibular system, housed in the vestibular labyrinth in the inner ear, senses head motion to estimate where the body is in space. It then uses this information to drive reflexes that are responsible for stabilizing gaze and posture. Five peripheral end organs send signals about motion to the vestibular nuclei and central nervous system. These organs are three semicircular canals, which sense angular head motion in three dimensions, and two otolith organs–the saccule and utricle–which sense vertical and horizontal linear head motion, respectively (Shepard & Schubert, 2016).

One major reflex driven by the vestibular system is the vestibulo-ocular reflex (VOR). The VOR stabilizes gaze during head motion by keeping a visual target locked on the fovea of the eye, where visual acuity is the highest. In broad terms, it causes the eyes to move equal and opposite to the head, allowing people to maintain focus on a target whenever they are moving (Shepard & Schubert, 2016).

The semicircular canals (SCC) are all orthogonal to each other, allowing them to sense angular head motion in three dimensions. Inside the ampulla of the SCC is a sensory organ called the crista, which contains stereocilia embedded into a gelatinous structure above called the cupula. Similar to the hair cells contained in the cochlea, the purpose of the vestibular hair cells is to convert mechanical energy into electrical energy. The crista is considered an accelerometer because it senses changes in head velocity. Vestibular afferents on the hair cells send motion signals along the superior vestibular nerve, to the vestibular nuclei in the brainstem, to motor neurons for cranial nerves III and VI, which innervate the medial and lateral rectus muscles on the eyes. In the example of a left head turn, vestibular afferents would send an excitatory signal along the left reflex pathway and an inhibitory signal along the right reflex pathway, ultimately resulting in a compensatory eye movement to the right (Shepard & Schubert, 2016).

B. Vestibular Stimuli

In a laboratory or clinic setting, the VOR can be elicited by rotating the participant in darkness. Sinusoidal harmonic acceleration (SHA) in the rotary chair is one method to stimulate the horizontal SCC using horizontal rotation. A SHA stimulus comprises three main properties: frequency, angular acceleration, and peak velocity. These properties interact with each other and impact the duration of the stimulus as well as the maximum angular displacement of the chair. Frequency (f) refers to the number of cycles per second the chair undergoes, where one cycle is a leftward rotation to maximum displacement and a rightward rotation back to initial resting position. The period, $t=1/f$, is the amount of time it takes to complete one cycle. Increasing the frequency will decrease the period (i.e., higher frequencies have shorter durations) (Zalewski, 2018).

Angular acceleration is the rate at which the velocity changes and for simple harmonic motion is mathematically defined as $a = 2\pi^2 f^2 D\sin(2\pi ft)$, where D = peak to peak displacement, t = time in seconds, and f = frequency. The angular acceleration for each stimulus frequency will depend on the target peak velocity. In this way, acceleration and displacement with a SHA stimulus are frequency-dependent— as frequency increases, stimulus duration decreases, displacement decreases, and acceleration must increase to reach peak velocity in a shorter amount of time.

In a SHA stimulus, maximum displacement is calculated at the point of a half cycle of rotation. The chair accelerates to peak velocity and then decelerates to 0 velocity at the maximum displacement, before accelerating and then decelerating in the opposite direction back to the initial resting position. It is calculated using the formula $x = D\sin(2\pi ft)/2$, where D = peak to peak displacement, f = frequency, and t = time in seconds.

The nystagmus observed from the rotation comprises two phases: a slow phase and a fast phase. The slow phase is when the eyes move equal and opposite to the direction the body is rotating. This is followed by a fast saccade wherein the eye corrects back to center before starting another slow phase. This nystagmus is quantified by its slow phase velocity (SPV), or how quickly the eyes move opposite the head as it turns. When the system is functioning appropriately, the SPV should be equal to the velocity of the body as it rotates (Shepard & Schubert, 2016).

C. Optokinetic System

Another system that works to stabilize gaze is the optokinetic system. Whereas the vestibular system is responsible for the VOR, the optokinetic system is responsible for optokinetic nystagmus (OKN). OKN is elicited when the viewer is stationary and the visual field around them moves. Like the VOR, the purpose of OKN is to hold a visual target on the fovea, but the main difference is that the VOR is elicited from self-motion and OKN is elicited from external motion (Shepard & Schubert, 2016).

When a stimulus of repeated moving objects takes up at least 90% of the visual field, the nystagmus is initially a result of smooth pursuit–the system through which the eyes track a smoothly moving object. The OKN takes a few seconds to develop and as the stimulus continues, the nystagmus comes from a combination of optokinetics and, primarily, smooth pursuit (Shepard & Schubert, 2016). When objects move horizontally, the image is tracked by the retina and that signal is sent to the ipsilateral thalamus, parts of the visual cortex, and the dorsolateral pontine nucleus, before crossing over to the contralateral flocculus and paraflocculus, as well as the vermis and fastigial nucleus in the cerebellum. At this point, the pathway overlaps with the horizontal VOR pathway, where the signal is sent to the vestibular nuclei, cranial nerves III and VI, and finally the medial and lateral rectus muscles on the eyes (Wong, 2008).

Unlike the VOR, the slow phase of OKN moves in the same direction as the external stimulus. When an object moves to the left, the slow phase of the nystagmus will also move to the left. As the stimulus continues, the viewer's eyes will perform a corrective saccade back to the center before starting another slow phase.

D. Optokinetic Stimuli

In clinical settings, a common tool used to elicit and assess OKN is a light bar, where a series of lights move horizontally across the bar and the patient is tasked with counting the lights as they pass through the center. However, Leigh and Zee (2006) found that in order to elicit proper OKN, the stimulus must fill at least 90% of the visual field and be able to produce the sensation of motion (i.e., circular vection). This suggests that light bars do not truly assess the optokinetic system, but rather primarily assess smooth pursuit. This is also true for optokinetic drums– striped drums spun on an axis in front of the patient's view–given that they do not take up the patient's full field of view.

For the best chance of tapping into the optokinetic system, the patient or participant's entire field of vision (FOV) should be stimulated. An example of this is an immersive stimulus, where the patient sits in a chair and a repeated stimulus (e.g., striped projections, striped cloth) physically spins around them in the chair, while they watch the stimulus move around them. However, it should be noted that the only true way to assess the optokinetic system without contamination from smooth pursuit is to assess optokinetic after nystagmus (OKAN). This phenomenon occurs when a person is exposed to a repeated external stimulus (e.g., an immersive optokinetic drum) for at least 30 seconds and is suddenly put into the dark. After 1 second, the smooth pursuit system no longer contributes and any continuing nystagmus is purely a product of the optokinetic system (Shepard & Schubert, 2016). Most clinical assessments of OKN are therefore primarily an assessment of smooth pursuit, or a combination of optokinetics and smooth pursuit.

E. Sensitivity of VOR and OKN

The VOR is sensitive to motion from .01 to 7.0 Hz (Cohen & Keshner, 1989), though it is most sensitive to motions above .1-.2 Hz and is often described as a high pass filter (Merfeld et al., 2005; Henn et al., 1976, Schweigart et al., 1997). The optokinetic system is considered a low pass filter, as it is most sensitive to lower-frequency motion (i.e., below 1 Hz) (Robinson, 1981; Schweigart et al., 1997).

In light, the optokinetic and vestibular systems work together to extend the range of sensitivity to both low and high frequency movements. Outside laboratory and clinic settings, people and the external environment both move simultaneously. Using the VOR and OKN together allows for gaze stabilization in real-world situations. The sensitivity of the two systems overlaps from about .01 to 1 Hz, allowing for use of both systems in conjunction during natural head motion. Below this frequency range, the optokinetic system dominates and above it, the vestibular system dominates (Karmali et al., 2014).

F. Vestibular Perception

Most tests performed in the clinic (e.g., rotary chair, calorics, and video head impulse testing (vHIT)) assess vestibular function through reflexes, most commonly the VOR. However, patients' sensation or perception of their symptoms may not always be reflected in these measures. Unlike reflexes, which are mediated at the level of the brainstem, vestibular perception requires higher order processing (i.e., the parieto-insular cortex) (Dieterich & Brandt, 2018). Psychophysics is the study of a physical stimulus and how the stimulus is perceived (Gelfand, 2010). Vestibular psychophysics studies the relationship between a vestibular stimulus (e.g., turning in a rotary chair) and self-motion perception beyond reflexes alone.

Most studies that employ vestibular psychophysics investigate motion perception at *threshold*, or the very smallest amount of movement that individuals accurately perceive. Many of these studies use forced-choice methods and an adaptive staircase procedure to determine threshold at a given point on a psychometric function. Similar to auditory research, average thresholds for normal individuals are affected by the frequency of the stimulus. In angular motion perception threshold studies, it has been found that thresholds are higher (i.e., not as sensitive) for lower stimulus frequencies compared to higher frequencies. A study published in 1989 by Benson and colleagues investigated normal individuals' detection thresholds of angular rotation. The researchers found that thresholds were better at higher stimulus frequencies. They further concluded, based on the gradient of their log-log plot of threshold over frequency, that these detection thresholds are primarily driven by angular velocity, with a smaller contribution from angular acceleration (Benson et al., 1989). Using sinusoidal angular motion, Grabherr et al. (2008) observed lower angular velocity thresholds as frequency increased from .05 to .2 Hz, with a plateau at .5 Hz and above. Similarly, Valko and colleagues (2012) observed higher angular velocity thresholds at .2 Hz (the lowest test frequency), with lower thresholds that plateaued beginning around .5-1 Hz. Priesol et al. (2014) studied motion in multiple planes in normal individuals and participants with idiopathic bilateral vestibulopathy. Thresholds in the yaw plane follow a consistent pattern with the other studies mentioned: thresholds decreased as frequency increased. Moreover, they found that patients with bilateral vestibular hypofunction maintained this pattern, but with a general overall increase in threshold. This body of evidence suggests that angular vestibular perception is more sensitive at high frequencies, consistent with vestibular physiology and the sensitivity of the VOR as a function of frequency.

Other studies have examined motion perception thresholds in other planes of motion and found similar patterns of frequency dependence. For example, Benson et al. (1986) found similar frequency characteristics for thresholds of horizontal linear motion and Merfeld and colleagues (2005) found similar results for perception of displacement for a roll tilt stimulus paradigm. Valko et al. (2012) and Priesol et al. (2014) found similar frequency characteristics in z- (i.e., up and down linear motion) and y-translation (i.e, left and right linear motion), though not for roll tilt.

Magnitude estimation is a psychophysical technique which assigns values to corresponding physical stimuli presented at *suprathreshold* levels. A common method of obtaining magnitude estimates is to assign a number to a reference stimulus, called the modulus, and have participants numerically rate other experimental stimuli relative to the modulus (Gelfand, 2010). Benson and Brown (1992) demonstrated that magnitude estimates, like perceptual thresholds, are frequency specific. Their results showed that participants' magnitude estimates of displacement angle and speed changed as a function of stimulus frequency when various parameters (e.g., angular velocity, acceleration, and displacement angle) were held constant. Interestingly, holding angular velocity constant resulted in an increase in magnitude estimates of speed with an increase in frequency, but holding angular acceleration constant had a much smaller effect on magnitude estimates of speed across all tested frequencies. This suggests that for their study, participants weighed angular acceleration more heavily than angular velocity when scaling stimulus intensity across various frequencies (Benson & Brown, 1992).

G. Visual Perception

The sensation of self-motion can be produced using a vestibular stimulus (i.e., head motion via a rotary chair). Self-motion perception may also be produced from auditory, somatosensory, or visual cues in the absence of a vestibular stimulus. For example, Keshavarz et al. (2014) elicited self-motion perception via auditory cues by rotating a sound signal, such as a church bell, around stationary individuals. Self-motion perception can also be induced through somatosensory cues, such as neck stimulation (Mergner et al., 1991).

Visually-induced motion perception has been much more thoroughly investigated. Optic flow is the pattern of stationary objects moving relative to the observer as the observer moves through space (Niehorster, 2021). For example, as an individual walks down a tree-lined path, the stationary trees will change their relative distance from the viewer as she moves forward, thus providing a cue for her self-motion. It has been found that in the absence of true self-motion, optic flow patterns can induce an illusion of self-motion called vection. Neuroimaging studies have shown that when optokinetic stimulation or optic flow patterns cause vection, areas in the early visual cortex are deactivated, which is not the case when optokinetic stimulation is perceived as external motion (Thilo et al., 2003).

Brandt, Dichgans, and Koenig (1973) elicited circular vection (i.e., the illusion of rotation) by rotating an immersive optokinetic drum continually around stationary participants, who could not tell the difference between the drum rotating and their body rotating. Kim and Palmisiano (2008) induced vection by presenting a radial optic flow pattern: squares appearing to expand out from the center of the screen. These radial optic flow patterns induced the sensation of forward linear translation, even though participants were stationary. The researchers were able to further enhance linear vection by applying "jitter," or a small amount of shake, to the visual display. Kim and Khuu (2014) performed a similar experiment, subjecting participants to a radial optic flow pattern of boxes on the screen that induced linear vection. They increased the sensation of vection by oscillating the display horizontally (i.e., clockwise and counterclockwise). Furthermore, Dichgans and Brandt (1978) elicited motion sickness in participants through pseudo-Coriolis stimulation, where circular vection was elicited by an optokinetic drum, and then the participant tilted their head out of the axis of rotation.

Visual perceptual threshold studies largely employ radial optic flow patterns, which induce a sense of linear motion in viewers (e.g., forward translation). Lamellar optic flow patterns, instead of expanding from the center, employ visual stimuli that are parallel to each other and move across the visual field. An example of a lamellar flow pattern is an optokinetic drum, which uses vertical bars to elicit OKN and induce circular vection. Crowell and Banks (1993) studied lamellar optic flow patterns to determine heading thresholds (i.e., the smallest difference in degree between two motions that is perceived by the viewer). They found that heading thresholds tended to decrease with increased speed of optic flow. Heading thresholds for lamellar optic flow were found to be ~5-20 degrees, depending on the speed of the visual stimulus. Warren et al. (1988) and Van den Berg (1992) studied heading direction using radial optic flow patterns and found that viewers were able to distinguish between two motions when those motions varied by 1-1.5 degrees, indicating that the visual system is very accurate as a cue for spatial orientation. Butler et al. (2015) studied heading thresholds using optic flow to induce forward linear motion and found thresholds of ~4-5 degrees, depending on the type of motion. When they used optic flow that changed at constant velocity, thresholds were significantly higher than when they used a raised cosine velocity (i.e., velocity gradually increased, peaked, and gradually decreased). This finding was likely a result of a raised cosine velocity stimulus being more realistic to natural head movement compared to a constant velocity stimulus.

Studies investigating *magnitude estimates* of visual stimuli are more relevant to the current study. Brandt and colleagues (1973) induced circular vection using an optokinetic drum with alternating vertical black and white stripes that rotated around the stationary viewer. They determined that magnitude estimates of speed matched the speed of the drum up to 90-120 deg/sec. At higher stimulus speeds, participants' magnitude estimates lagged behind stimulus speed, indicating a "saturation" of circular vection at high velocities (Brandt et al., 1973). Dichgans and Brandt (1973) studied magnitude estimates of Coriolis stimuli, evoked by tilting the head while either the viewer or the visual surround rotates. When the viewer rotates, the resulting perception of motion is called the Coriolis effect. When the visual surround rotates, the perception of motion is called the pseudo-Coriolis effect. Their results showed that magnitude estimates of both the coriolis and pseudo-coriolis effect increased with an increase in angular velocity of the drum or chair. However, magnitude estimates of the coriolis effect were consistently higher than those of the pseudo-coriolis effect. This suggests that self-motion perception is scaled with both visual and vestibular stimuli, but that the effect is stronger for the vestibular system (Dichgans & Brandt 1973). Larish and Flach (1990) demonstrated a similar effect using a visual display that evoked a sense of forward linear translation. They found that magnitude estimates of speed increased as two different measures of visual stimulus velocity (edge rate and global flow rate) increased. In other words, as the visual scene's velocity increased, participants' magnitude estimates did, as well. Other variables that have been shown to increase magnitude estimates of speed are spatial frequency (Diener et al., 1976) and color contrast (Patterson & York, 2009) of visual targets.

Studies investigating magnitude estimates of distance using visual stimuli, specifically visual stimulation inducing a sense forward linear translation in the viewer, have conflicting findings. Frenz and Lappe (2005) induced a perception of forward linear translation in their participants using 1) a virtual representation of the ground and a horizon in the distance, 2) white dots clustered densely around a horizon line against a black background, 3) and white dots scattered less densely below a horizon line against a black background. The researchers found that in all three virtual environments, participants underestimated their perceived distance, with the ground scene eliciting the least accurate estimates (Frenz & Lappe, 2005). Similarly, Sun et al. (2004) found that when optic flow and vestibular information were presented together, magnitude estimation of perceived distance was underestimated compared to vestibular-only conditions. Harris et al. (2000) had participants estimate distance moved using vestibular and visual cues. Subjects were physically translated in a chair and provided a vestibular target for distance traveled. They were then visually translated using an optic flow pattern and asked to indicate when they reached the vestibular target. Results showed that they consistently underestimated the distance traveled in the visual scene compared to the vestibular target. Interestingly, when the target presented before the visual stimulus was presented through the visual modality, magnitude estimations of distance were quite accurate (Harris et al., 2000).

Other studies, however, have found an overestimation of distance using visual information compared to vestibular. Redlick et al. (2001) presented participants with visual targets in a virtual corridor followed by a radial optic flow pattern associated with the corridor. They were asked to indicate when they reached the targets by estimating distance traveled in the from the optic flow. At faster accelerations (i.e., > .1 m/sec^2), participants were accurate. However, at lower acceleration rates, they overestimated how far they traveled in the virtual corridor. That they were accurate in some of the motions when the target was presented visually, rather than through true vestibular motion, aligns with Harris' et al. (2000) findings that magnitude estimates of distance are accurate when both the target and test motion are presented visually.

H. Virtual reality

Virtual reality (VR) is an innovative advancement in testing optokinetic stimulation for several reasons. First, circular vection increases with an increase in the stimulus area and is stronger for stimulation of the peripheral retina when using an optokinetic drum (Dichgans & Brandt, 1978). The functional sensitivity hypothesis states that when humans perceive self-motion from optic flow, the central retina is sensitive to both radial and lamellar optic flow, but the periphery is more sensitive to lamellar optic flow (Warren & Kurtz, 1992). Therefore, when presenting lamellar optic flow (e.g., parallel vertical lines moving horizontally to induce circular vection), having as wide a FOV as possible will promote circular vection by stimulating the viewer's periphery. Second, VR can provide an immersive, realistic visual stimulus. Keshner and Kenyon (2009) used virtual reality to assess postural stability when vestibular and visual cues were manipulated. They found that when vestibular input was compromised by having participants stand on a rod, as opposed to a stable base, they relied heavily on visual input. Specifically, when they experienced vestibular instability, but had access to a wide FOV (e.g., 150 degrees), they did not lose as much postural control as with a narrower

FOV. In other words, they could not ignore visual input from a wide FOV and used it to adapt their posture. The researchers determined that VR was a useful tool in balance training and produced "measurable rehabilitation outcomes" (Keshner & Kenyon, 2009). Third, magnitude estimates of circular vection under a VR headset demonstrate that vection increases as display speed increases. Kirollos and Herdman (2021) presented a virtual optokinetic drum under a VR headset and found that as the velocity of the virtual drum increased, so did participants' magnitude estimates. Taken together, these findings suggest that virtual reality can produce a high fidelity optokinetic stimulus.

I. Clinical significance

There is appreciable clinical significance in assessing vestibular function using psychophysical techniques, rather than testing based on reflexes alone. Merfeld et al. (2005) hypothesized that two different neural mechanisms likely contribute to VOR and perception, as one is a brainstem mediated pathway, and the other is cortical. Chang et al. (2014) compared VOR gain and phase to velocity thresholds at .5 Hz in normal participants and found no significant correlations between reflexes and perception for any individuals, regardless of age. Similarly, Lewis et al. (2011) observed differences in the VOR and perceptual thresholds in a pathological population. Specifically, perceptual thresholds in patients with vestibular migraine were reduced in the mid-frequencies compared to normal individuals, despite VOR measures within normal limits. Existing research on perceptual thresholds and the VOR thus indicate that the two mechanisms do not always align, and assessing only vestibular reflexes may cause certain pathologies, especially those originating from the central nervous system, to go undetected during vestibular testing.

During audiometry, clinicians not only measure detection thresholds, but also word recognition tasks at suprathreshold presentation levels. Similarly, magnitude estimation of vestibular stimulation may be a particularly useful psychophysical technique in determining functional vestibular deficits. It has been reported that adults' subjective perception of suprathreshold motion are not always reflected in reflexive testing. For example, Piker et al. (2020) studied individuals who did not perceive motion during warm caloric testing, despite generating appropriate SPV during nystagmus. These individuals were more likely to fall during condition five of computerized dynamic posturography, which isolates the vestibular system's role in maintaining postural stability. Furthermore, those same individuals were more likely to have cognitive deficits, such as poor visuospatial working memory (Piker et al., 2020). In 2014, Piker and colleagues also studied how patients described their symptoms compared to how they presented clinically in reflex testing. The researchers found that despite having a higher rate of BPPV, adults over the age of 65 were less likely to describe their symptoms as true vertigo, which is typically what clinicians expect when diagnosing BPPV (Piker et al., 2014).

The clinical significance of implementing virtual reality to elicit OKN is that it provides an immersive, more realistic experience than a light bar or optokinetic drum, for example. VR provides a wider field of vision, which allows the optokinetic system to dominate the response, as opposed to smooth pursuit (Shepard & Schubert, 2016). The wide FOV provided by a VR stimulus also promotes circular vection, since it has been argued that the retinal periphery controls perception of vection for lamellar optic flow (e.g., for perceived rotation around the yaw axis) (Crowell & Banks, 1993). Keshner and Kenyon (2009) argued that for vestibular rehabilitation purposes, VR allowed patients to practice realistic, functional exercises in a safe and controlled environment. Given its utility in vestibular rehabilitation, it has the potential to be diagnostically useful, as well. Kirollos and Herdman (2021) used a VR headset to present constant velocity stimulations of a virtual optokinetic drum. Since the advantage of VR is the potential for realistic visual scenes, it has clinical potential in being able to provide an optokinetic stimulus equal to physical rotation in a rotary chair, rather than using an optokinetic drum.

J. Purpose

The purpose of this study was to:

1. Compare magnitude estimates from vestibular stimulation to visual stimulation across multiple suprathreshold frequencies.

2. Assess the feasibility of using virtual reality to provide an optokinetic stimulus equal to that of the rotary chair at frequencies where both systems are sensitive.

II. Methods

A. Participants

17 participants aged 20-35 (mean: 21.8; SD: 3.6) were recruited from James Madison University for this study. Inclusion criteria were adults aged 18-35 with no known history of vestibular impairment. Exclusion criteria were individuals with complaints of imbalance, with a history of otological disease, and individuals taking vestibulotoxic medication as determined by a questionnaire completed prior to participation.

B. Stimuli

Table 1. Stimulus Conditions in Vestibular and Optokinetic Modalities.

Frequency (Hz)	.08	Peak Velocity (deg/sec)	30	45		75	90
	.16		30	45	60*	75	90
	.32		30	45		75	90

*Baseline condition only

Vestibular Stimulation

Participants were exposed to 13 sinusoidal harmonic accelerations (SHA) in the yaw plane using the Micromedical Technologies System 2000 Rotational Vestibular Chair (Chatham, IL). The vestibular stimuli consisted of 1 baseline and 12 experimental conditions. See Table 1 for stimulus conditions.

Optokinetic Stimulation

A three-step process of video recording, computer programming, and exporting to a standalone virtual reality (VR) device allowed us to recreate a SHA stimulus under a virtual environment to compare visual and vestibular motion perception. To record the physical stimulus, a pair of BG3.0USB top mounted video goggles for the Micromedical Technologies System 2000 Rotational Vestibular Chair (Chatham, IL) were secured to the headrest of the chair using the side-mounted Velcro straps attached to the goggles. A GoPro Hero 3 Silver Edition (San Mateo, CA) with a video resolution of 1080p and 30 fps, 11 Megapixels (MP), photo burst of 10 photos per second, and time Lapse of 0.5 seconds was positioned inside the video goggles to give a first-person frame of reference during each rotation (see Figure 1A). Videos of sinusoidal rotation were then recorded at the same baseline and experimental frequencies as the vestibular stimulation (see Table 1).

Following the recording of each condition, the video files were uploaded into Unity Real-Time 3D Development Platform (Unity Technologies, Copenhagen, Denmark) and a custom program was written in the software to visually distort each recording and overlay vertical bars in the foreground of the video. The vertical bars and distortion were necessary so that all visual landmarks were removed from the video image while still providing the same optic flow information (i.e., frequency and peak velocity) of a moving stimulus (see Figure 1B).

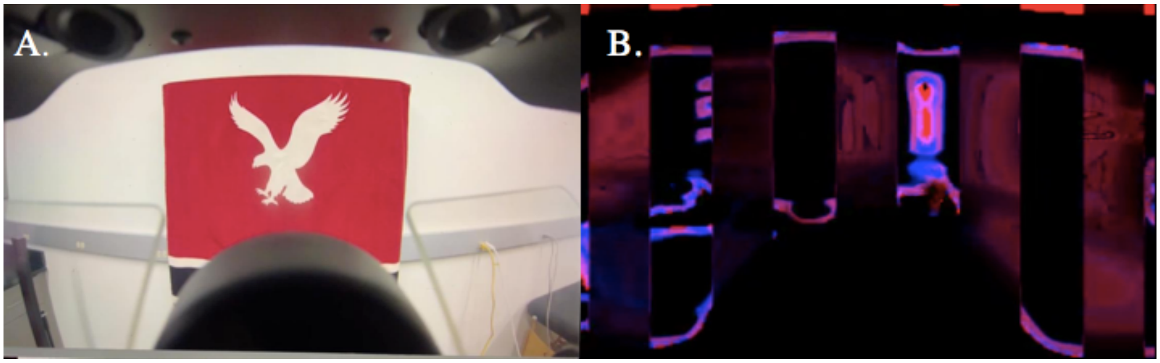


Figure 1. Raw and Final Visual Stimulus. A, Raw image taken from a GoPro positioned inside the rotational chair video goggles to record angular SHA stimuli. B, Image recorded from the GoPro after it was distorted to eliminate visual cues, such as the bird on the wall shown in A., but maintain an optic flow pattern. This is the version of the video that participants were exposed to under VR.

Lastly, the custom program containing the edited videos was exported using Unity's build support module to a standalone Oculus Go VR headset (First generation, Facebook Technologies, Menlo Park, CA). The VR headset was used to present a virtual recreation of SHA rotation to all participants in order to compare motion perception across sensory modalities (i.e., vestibular and visual motion perception).

C. Procedure

This study employed a within-subjects design, where all participants were exposed to both vestibular and optokinetic stimulation. Each modality was delivered in a block, which took 30-45 minutes to complete. Both blocks of testing were administered within the same test session. Whether participants completed the vestibular or optokinetic block first was alternated. To avoid order effects, the order of experimental conditions within each test block was randomized. However, for both test blocks the baseline conditions were delivered first.

For vestibular stimulation, participants were secured in the rotational chair using the seatbelt and velcro head restraints. The lights in the testing room were turned off and they wore the BG3.0USB top mounted video goggles with blackout visors placed over them. They confirmed that no light was visible through the goggles before each rotation. To mask any auditory cues to speed or spatial orientation, white noise was presented at a level that the participant confirmed was "loud but comfortable" through an iPod touch and Apple corded earbuds (Cupertino, CA).

For optokinetic stimulation, participants were secured in the rotational chair with the seatbelt. The lights in the testing room were turned off and they wore the Oculus Go VR headset and held the corresponding remote control. The chair remained stationary during all optokinetic testing and participants watched the videos described previously under the VR headset. In between conditions, the researcher selected the video corresponding to the next randomized condition in the VR headset. Once the participant was ready, they would put the VR goggles back on and start the video. Similar to the vestibular block, the participant listened to white noise during optokinetic stimulation to block any auditory cues. Participant set-up for each test block is demonstrated in Figure 2.

Figure 2. Participant Set-Up in Vestibular and Visual Modalities. A, Participant set-up in vestibular modality with a pair of top mounted video goggles with blackout visor and earbuds playing white noise to block any external visual or auditory cues. B, Participant set-up for optokinetic modality with an Oculus Go head-mounted VR display and earbuds to block auditory cues.

Magnitude Estimation

For both vestibular and optokinetic modalities, participants provided their magnitude estimates of speed and spatial orientation using a visual analog scale (see Figure 3). A baseline stimulus of 0.16 Hz at 60 deg/sec peak velocity was presented first and assigned a modulus of “50” for speed. The perceived speed of all subsequent experimental conditions was then compared relative to the modulus. For example, if they felt they went twice as fast as the baseline condition, they would rate the speed at “100” on the visual analog scale. Spatial orientation was defined as the furthest point that they turned, in degrees, before returning back to their initial resting position. Since spatial orientation was estimated using absolute units, those magnitude estimates were not compared to the baseline condition. Participants provided their magnitude estimates of speed and spatial orientation immediately after each condition.

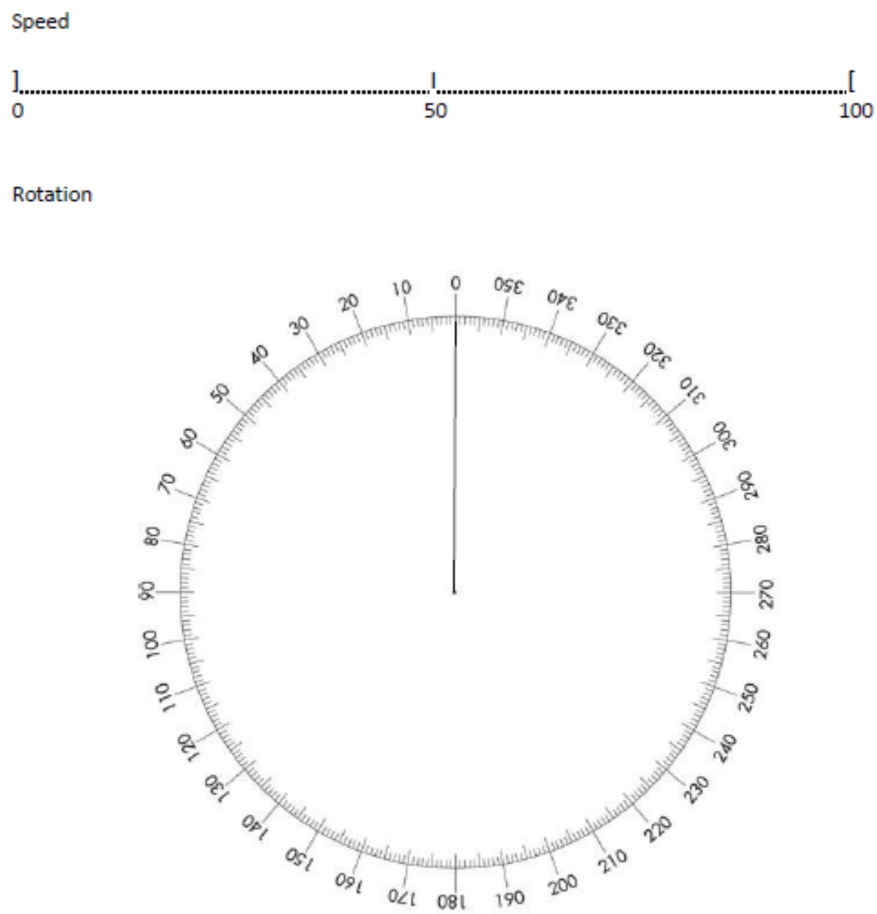


Figure 3. Visual Analog Scale. This scale was provided to participants after each condition. They rated their speed in arbitrary units on the top scale and their spatial orientation angle on the bottom scale.

D. Statistical Analysis

A three-way repeated measures analysis of variance (ANOVA) was performed to determine the effect of modality (vestibular versus optokinetic), frequency (0.08, 0.16, and 0.32 Hz), and peak velocity (30, 45, 75, and 90 deg/sec) on magnitude estimates of speed. A second three-way repeated measures ANOVA was performed to determine the effect of modality, frequency, and peak velocity on magnitude estimates of spatial orientation.

III. Results

17 participants were recruited to participate in the study. One participant dropped out immediately due to motion sickness evoked by the rotary chair and another participant could not complete all testing due to an equipment malfunction with the VR goggles. These two participants' data are not included in analysis (n = 15).

A. Speed Magnitude Estimates

For each experimental condition, subjects rated their speed on a visual analog scale ranging from 1-100 in comparison to a modulus of 50 assigned to the baseline condition, .16 Hz at 60 deg/sec. Means and standard deviations for magnitude estimates for both vestibular and visual modalities are listed in Table 2.

Figure 4 shows individual and average magnitude estimates of speed for all conditions in the vestibular modality. Figure 5 shows individual and average magnitude estimates of speed for all conditions in the visual modality. In general, as peak velocity increased, magnitude estimates of speed increased at all tested frequencies.

A repeated measures ANOVA was completed to determine the effect of modality, frequency, and peak velocity on the participants' magnitude estimates of speed. There was no significant main effect of modality ($F(1, 14) = .044$, $p = .837$). There were significant main effects of frequency ($F(2, 13) = 9.645$, $p = .003$) and peak velocity ($F(3, 12) = 50.266$, $p = <.001$) on magnitude estimates of speed. Furthermore, there were no significant interactions between any dependent variables (i.e., modality, frequency, or peak velocity).

There was no significant difference between magnitude estimates of speed for vestibular versus visual stimulation. This is reflected in the high degree of overlap between magnitude estimates of both modalities across all tested frequencies and peak velocities (see Figure 6). These findings suggest that the sensation of speed created under the VR goggles was similar to that created by physical motion in the rotary chair.

Because there was no significant main effect of modality, data from both modalities were combined in Figures 7 and 8, which demonstrate the significant main effects of frequency and peak velocity, respectively. In general, as frequency increased, participants' magnitude estimates of speed also increased. In post hoc pairwise comparisons, this increase in magnitude estimates was significant between .08 and .32 Hz ($p < .001$) and .16 and .32 Hz ($p < .001$) (see Figure 7). Furthermore, as peak velocity increased, so did magnitude estimates of speed. In post hoc analysis, magnitude estimates significantly increased between all peak velocities ($p < .001$), except for 75 and 90 deg/sec ($p = .108$) (see Figure 8).

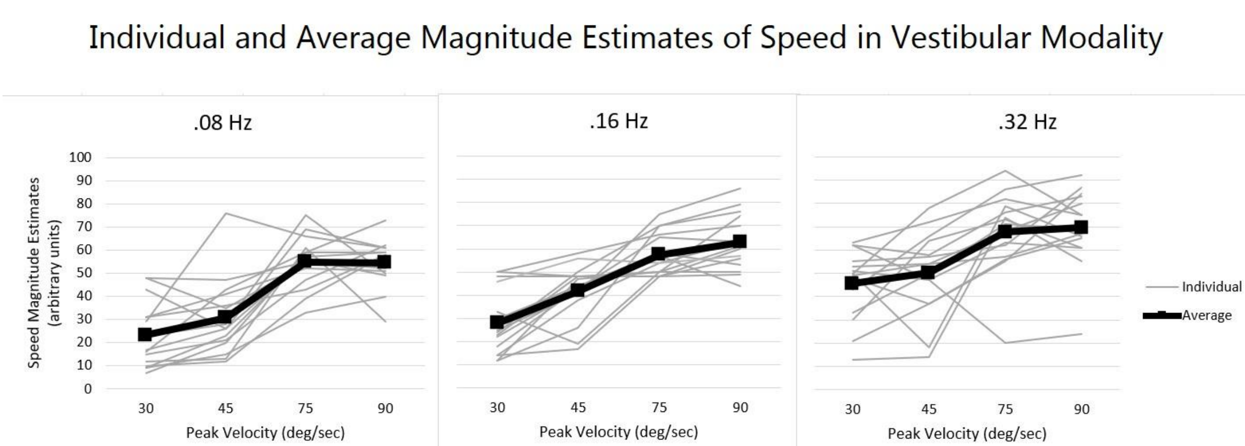


Figure 4. Individual and Average Magnitude Estimates of Speed in Vestibular Modality. These line graphs demonstrate the effect of peak velocity on individual (gray lines) and average (black line) magnitude estimates of speed under vestibular stimulation.

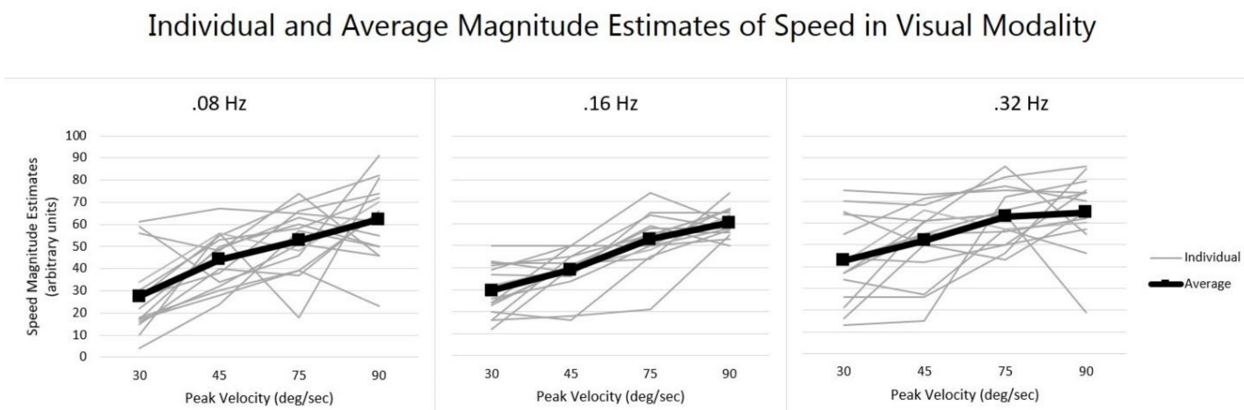


Figure 5. Individual and Average Magnitude Estimates of Speed in Visual Modality. These line graphs demonstrate the effect of peak velocity on individual (gray lines) and average (black line) magnitude estimates of speed under visual stimulation.

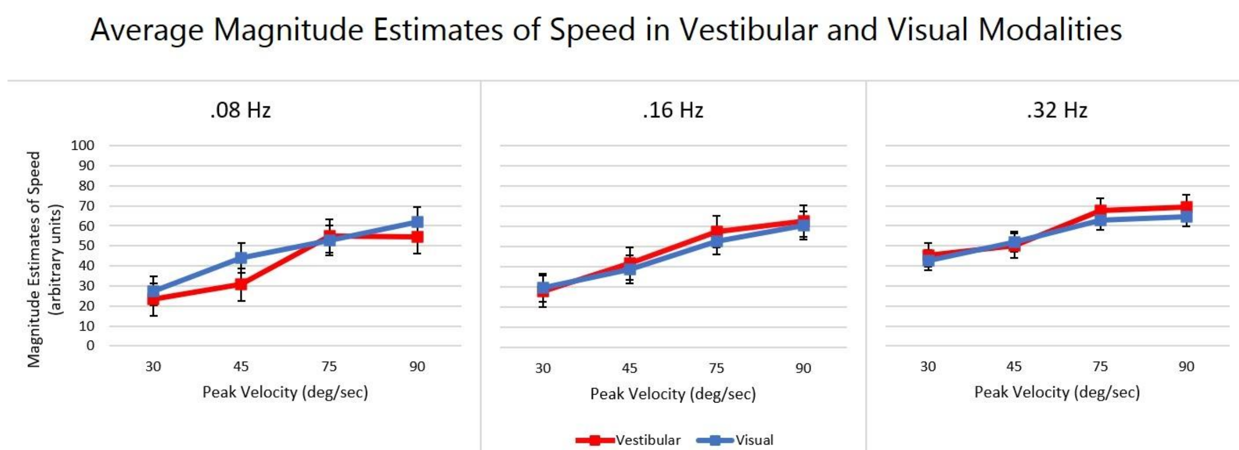


Figure 6. Average Magnitude Estimates of Speed in Vestibular (red) and Visual (blue) Modalities. There was no significant difference between magnitude estimates under vestibular stimulation compared to visual stimulation.

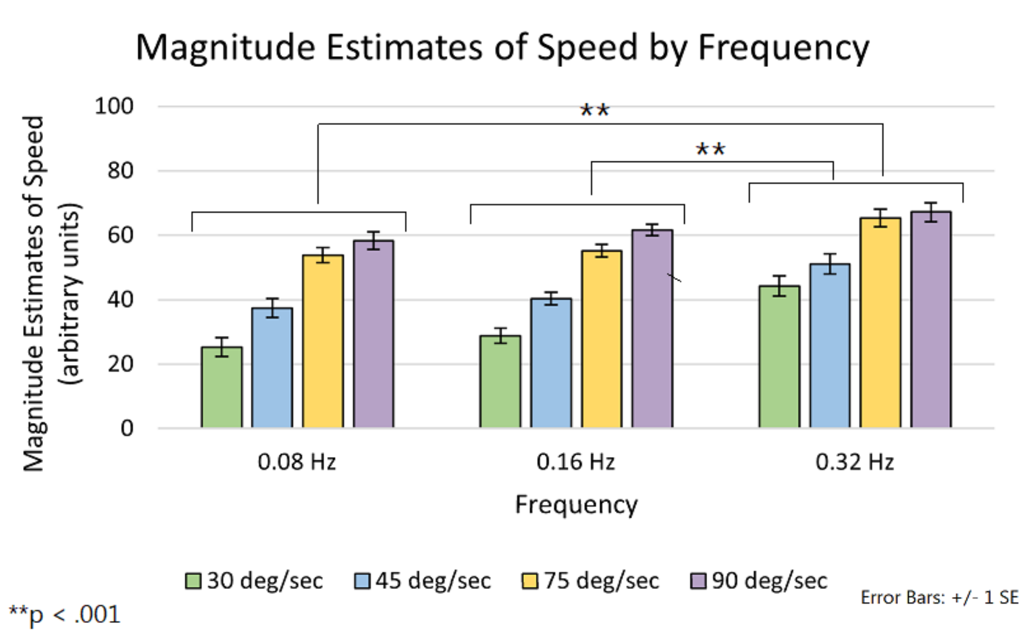


Figure 7. Magnitude Estimates of Speed by Frequency. No main effect of modality was found, so visual and vestibular magnitude estimates were combined.

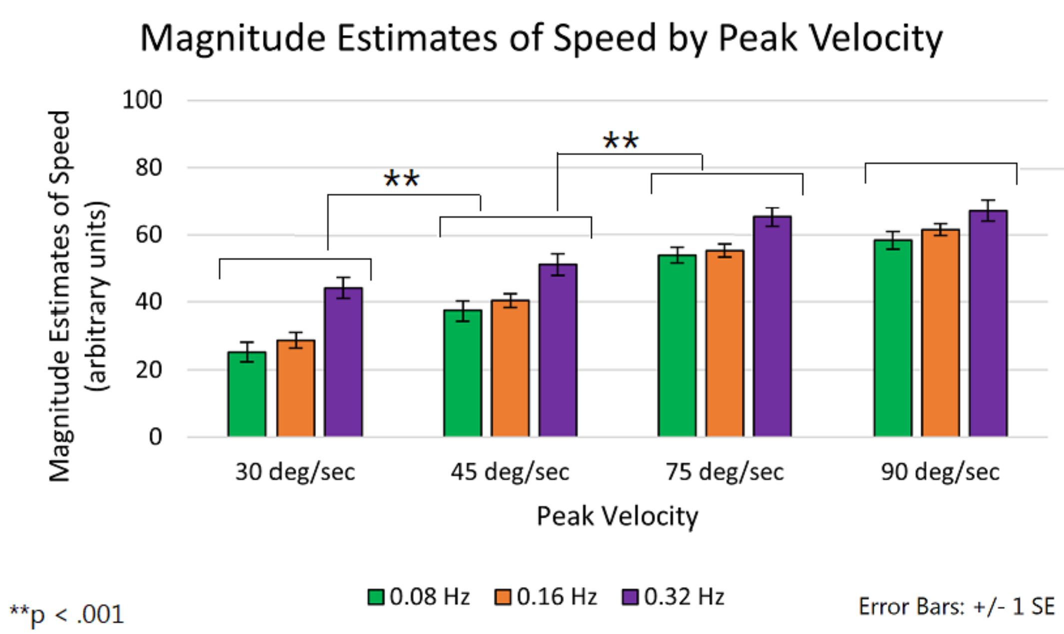


Figure 8. Magnitude Estimates of Speed by Peak Velocity. No main effect of modality was found, so visual and vestibular magnitude estimates were combined.

B. Spatial Orientation Magnitude Estimates

For each condition, participants rated their spatial orientation, defined as the furthest distance in degrees the rotational chair turned (or they felt the chair turn under virtual reality) before returning to its resting position. Means and standard deviations for spatial orientation magnitude estimates in vestibular and visual modalities are listed in Table 3.

Individual magnitude estimates of spatial orientation are shown in Figure 9, where red dots show the spatial orientation estimates from vestibular stimulation and blue dots represent spatial orientation estimates from visual stimulation. The black line in each plot represents the true spatial orientation angle.

A repeated measures ANOVA was completed to determine the effect of modality, frequency, and peak velocity on the participants' magnitude estimates of spatial orientation. There were significant main effects of modality ($F(1, 14) = 60.034$, $p = <.001$), frequency ($F(2, 13) = 59.111$, $p = <.001$), and peak velocity ($F(3, 12) = 80.979$, $p= <.001$) on magnitude estimates of spatial orientation. Furthermore, there were significant interactions between modality and frequency ($F(2, 13) = 5.746$, $p = .016$), modality and peak velocity ($F(3, 12) = 7.648$, $p = .004$), and frequency and peak velocity ($F(6, 9) = 32.053$, $p = <.001$). There was not a significant three-way interaction between modality, frequency, and peak velocity ($F(6, 9) = .951$, $p = .506$).

Figure 10 demonstrates the effect of modality and frequency on spatial orientation magnitude estimates. For both modalities, spatial orientation magnitude estimates decreased with increasing frequency. Post hoc pairwise comparisons revealed that this reached significance across all frequencies ($p < .001$). However, the magnitude estimates made under visual stimulation consistently underestimate those made under vestibular stimulation.

Figure 11 demonstrates the effect of modality and peak velocities on spatial orientation magnitude estimates. For both modalities, spatial orientation magnitude estimates increased with increasing frequency. Post hoc pairwise comparisons revealed that this reached significance across all peak velocities ($p < .001$). Again, the magnitude estimates made under visual stimulation consistently underestimate those made under vestibular stimulation.

Figure 12 demonstrates the effect of frequency and peak velocity on spatial orientation magnitude estimates for the vestibular (A) and visual (B) modalities separately. Greater peak velocities across a constant frequency resulted in larger spatial orientation magnitude estimates and greater frequencies across a constant peak velocity resulted in smaller spatial orientation magnitude estimates. This was true for both modalities, though visual magnitude estimates were smaller than vestibular magnitude estimates.

For spatial orientation, magnitude estimates could further be analyzed by how accurate they were to true spatial orientation. Figure 13 demonstrates all individual magnitude estimates versus the true spatial orientation angle for vestibular (red) and visual (blue) modalities. The lines of best fit for each modality are also displayed on the graph. The green line demonstrates the line of equality, where the magnitude estimate equals the true spatial orientation angle. Participants were more accurate at estimating spatial orientation from a vestibular stimulus compared to a visual one.

Individual spatial orientation error in degrees was calculated for each participant by subtracting the true angle the chair or visual stimulus turned from the magnitude estimate. Negative numbers therefore indicate that the participant underestimated how far they turned and positive numbers indicate that the participant overestimated how far they turned. A spatial orientation error of zero indicates the participant accurately estimated the degree they turned. Figure 14 shows individual spatial orientation errors and the average for each condition in the two modalities. Average spatial orientation errors were more negative for the visual modality compared to the vestibular modality for all conditions except .32 Hz at 30 dps, suggesting that for the most part, participants underestimated their spatial orientation under the virtual reality goggles.

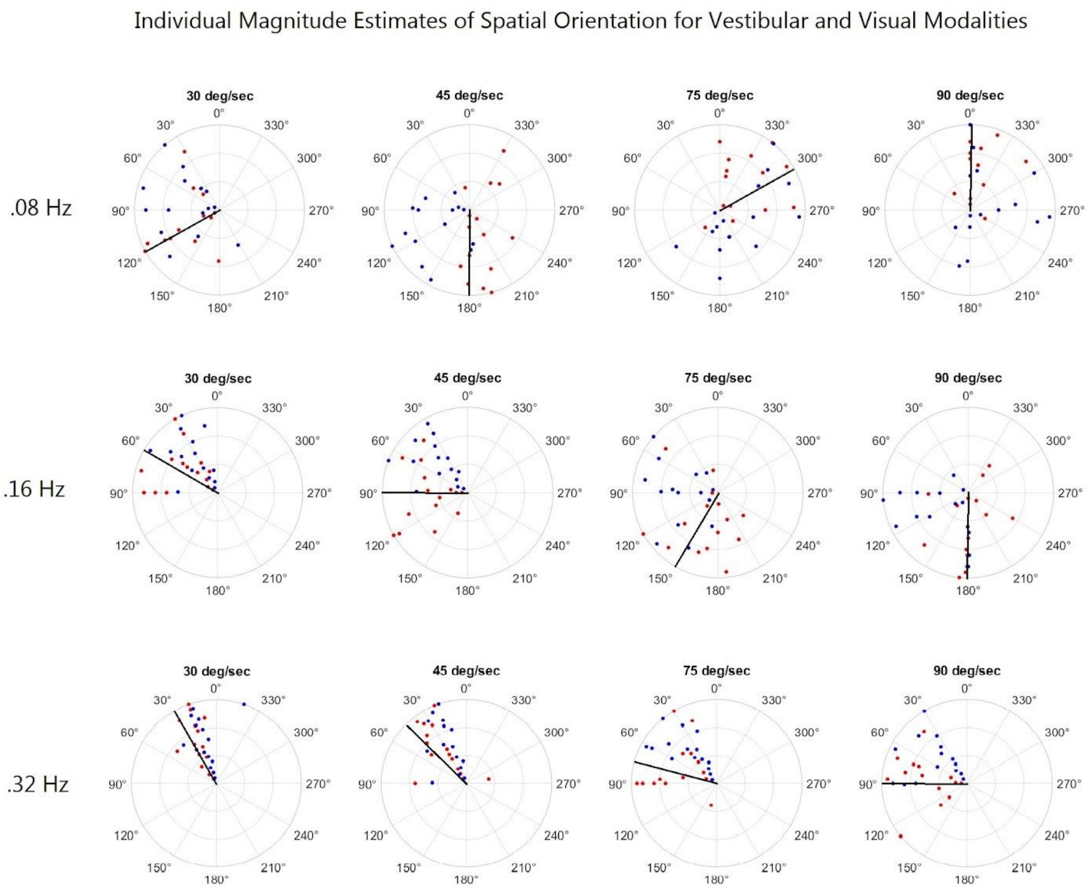


Figure 9. Individual Magnitude Estimates of Spatial Orientation in Vestibular (red dots) and Visual (blue dots) Modalities. The rotary chair and the video under VR always started at an initial position of 0 degrees. The chair then turned counterclockwise before returning back to the initial position. The black lines represent the true angle of rotation the chair or visual stimulus reached before returning back to the initial position. The magnitude estimates represent the furthest point that participants felt the chair or the visual stimulus move before returning to the initial position.

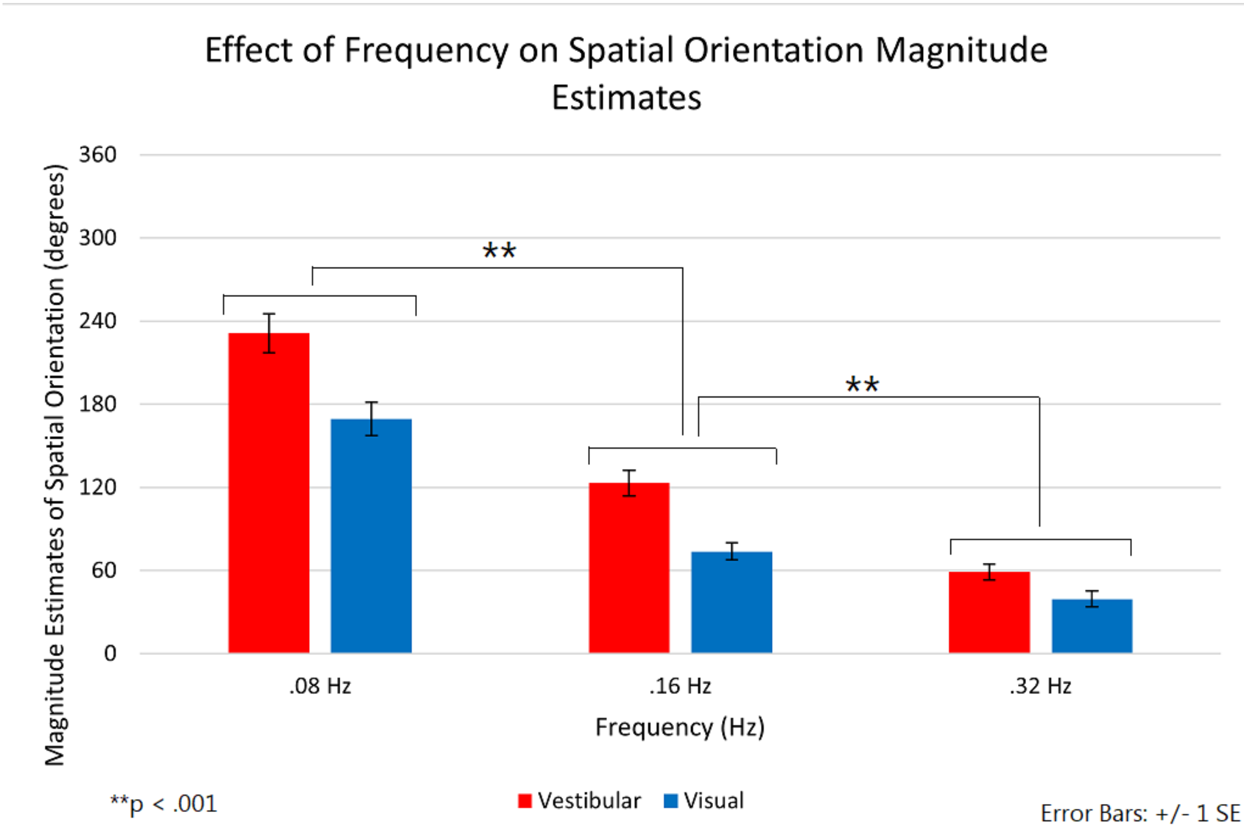


Figure 10. Effect of Frequency on Spatial Orientation Magnitude Estimates. Bars represent average magnitude estimates at each frequency under vestibular (red) stimulation and visual (blue) stimulation. Post hoc pairwise comparisons revealed a significant decrease in magnitude estimates with increasing frequency ($p < .001$).

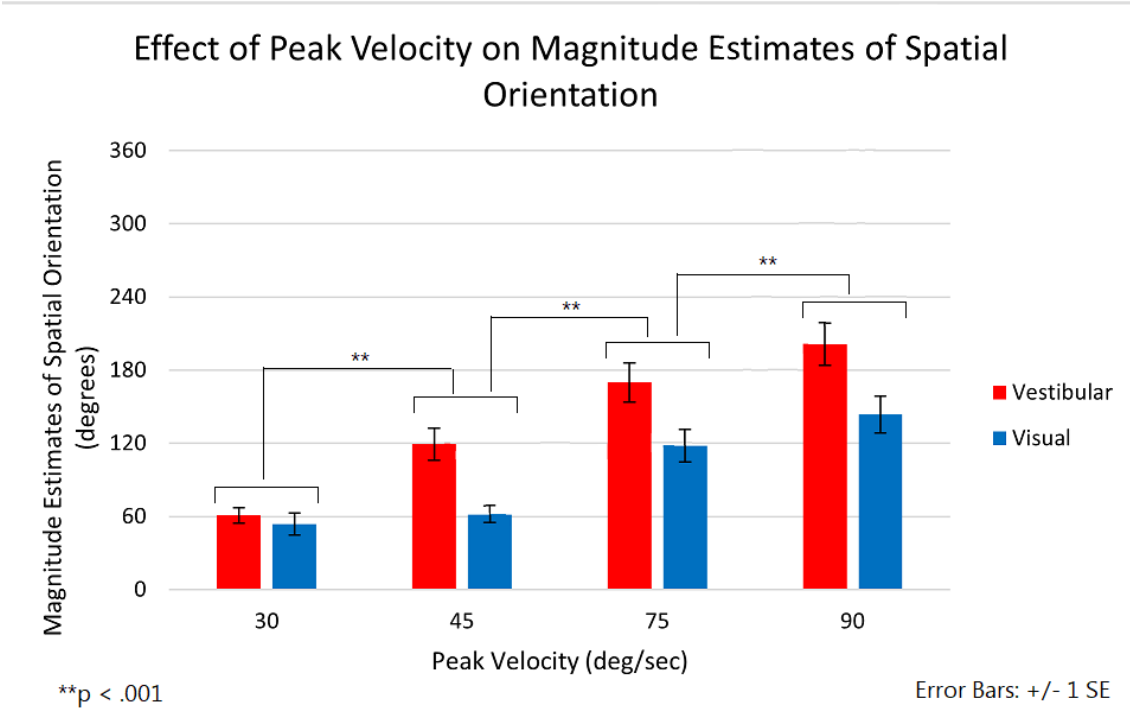


Figure 11. Effect of Peak Velocity on Spatial Orientation Magnitude Estimates. Bars represent average magnitude estimates at each peak velocity under vestibular (red) stimulation and visual (blue) stimulation. Post hoc pairwise comparisons revealed a significant increase in magnitude estimates with increasing frequency (p < .001).

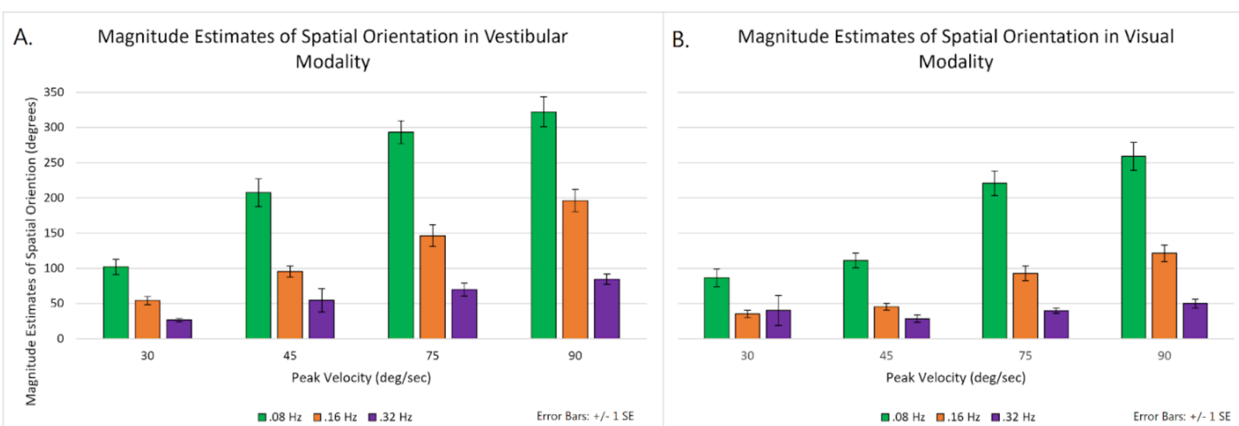


Figure 12. Effect of Frequency and Peak Velocity on Spatial Orientation Magnitude Estimates in A) Vestibular and B) Visual Modalities.

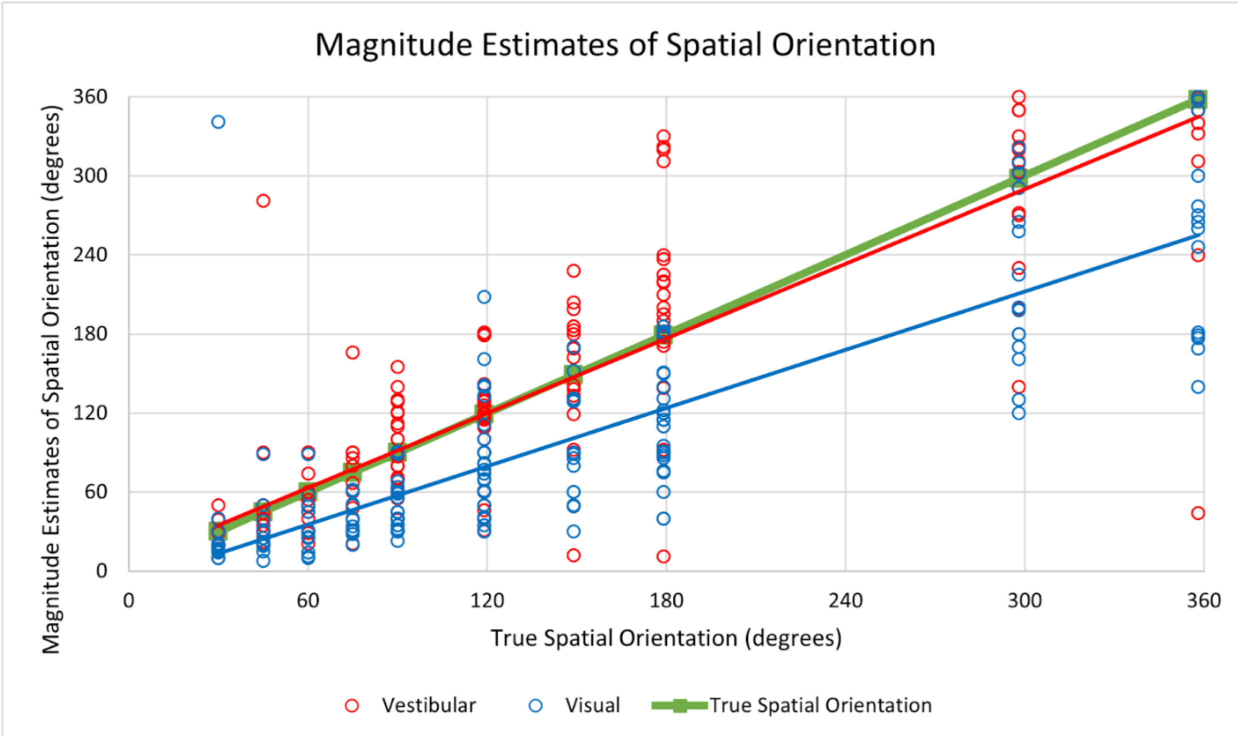
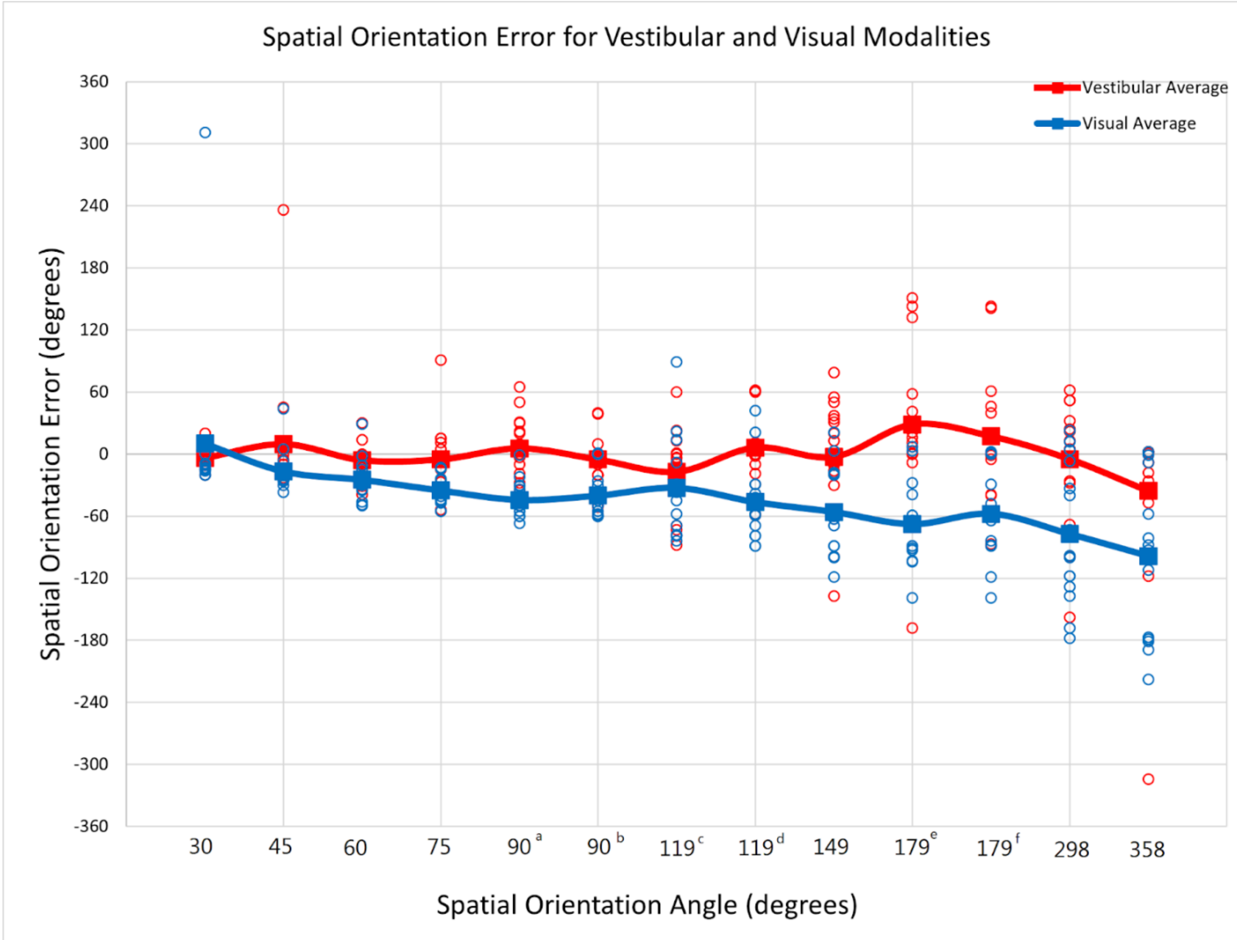


Figure 13. Magnitude Estimates of Spatial Orientation. Individual magnitude estimates of spatial orientation for vestibular (red dots) and visual (blue dots) modalities. Lines of best fit were superimposed to demonstrate trends for each modality. The green line represents the line of equality, where magnitude estimates of spatial orientation equal true spatial orientation.



[a].16 Hz at 45 deg/sec [c].08 Hz at 30 deg/sec [e].08 Hz at 45 deg/sec
[b].32 Hz at 90 deg/sec [d].16 Hz at 60 deg/sec [f].16 Hz at 90 deg/sec

Figure 14. Spatial Orientation Error for Vestibular and Visual Modalities. Individual (open circles) and average (solid squares) spatial orientation errors for vestibular (red) and visual (blue) modalities. Due to the interaction between frequency and peak velocity, some experimental conditions created the same spatial orientation angle (e.g., .16 Hz at 45 deg/sec and .32 Hz at 90 deg/sec both yielded a spatial orientation angle of 90 degrees). These spatial orientations are plotted separately from each other on the x-axis. Spatial orientation error was calculated by subtracting the true spatial orientation in degrees from the magnitude estimate in degrees. Negative numbers represent an underestimation of spatial orientation.

Table 2. Mean (SD) Magnitude Estimates of Speed (arbitrary units) by Condition.

	.08 Hz		**.16 Hz**		**.32 Hz**	
	Vestibular	**Visual**	**Vestibular**	**Visual**	**Vestibular**	**Visual**
30 deg/sec	23.2 (14.4)	27.5 (17.9)	28.1 (14.2)	29.7 (11.7)	45.5 (15.0)	42.8 (19.6)
45 deg/sec	30.8 (16.6)	44.0 (12.7)	41.7 (12.2)	39.0 (10.2)	50.2 (18.0)	52.0 (17.5)
75 deg/sec	55.0 (11.2)	52.7 (15.1)	57.5 (9.3)	52.9 (12.0)	67.7 (17.4)	62.9 (13.2)
90 deg/sec	54.5 (10.3)	62.1 (17.5)	62.7 (12.1)	60.5 (6.4)	69.6 (16.6)	64.8 (16.9)

Table 3. Mean (SD) Magnitude Estimates of Spatial Orientation (degrees) by Condition.

	.08 Hz			**.16 Hz**			**.32 Hz**		
	True	**Vestibular**	**Visual**	**True**	**Vestibular**	**Visual**	**True**	**Vestibular**	**Visual**
30 deg/sec	119	101.9 (42.2)	86.4 (47.7)	60	54.1 (23.2)	35.1 (20.5)	30	26.3 (10.5)	40.2 (83.6)
45 deg/sec	179	207.6 (77.2)	111.3 (40.4)	90	95.5 (31.7)	45.7 (17.7)	45	54.6 (64.6)	28.3 (19.6)
60 deg/sec				119	125.3 (40.3)	75.25 (37.7)			
75 deg/sec	298	293.2 (62.6)	220.7 (66.4)	149	146.4 (59.1)	93.1 (41.1)	75	69.9 (35.8)	39.8 (14.3)
90 deg/sec	358	322.4 (83.2)	259.4 (76.6)	179	196.3 (62.1)	121.3 (45.4)	90	84.8 (28.3)	49.9 (23.3)

IV. Discussion

The purpose of this study was to:

1) Compare magnitude estimates from vestibular stimulation to visual stimulation across multiple suprathreshold frequencies, and

2) Assess the feasibility of using virtual reality to provide an optokinetic stimulus equal to that of the rotary chair at frequencies where both systems are sensitive.

A. Magnitude Estimation Across Multiple Frequencies in Vestibular vs Visual Modalities

Speed Magnitude Estimates

A repeated measures ANOVA was completed to determine the effect of modality, frequency, and peak velocity on the participants' magnitude estimates of speed. There was no significant effect of modality on speed magnitude estimates, which suggests that the sensation of speed created by watching the visual stimulus under VR goggles was equal to the sensation of speed evoked by physically turning in the rotary chair.

The repeated measures ANOVA revealed a significant main effect of frequency, suggesting that as frequency increased, so did participants' magnitude estimates of speed (see Figure 7). This aligns with previous studies that investigated vestibular perceptual thresholds in the yaw plane, which found an increased sensitivity to motion with increasing frequency (Benson et al., 1989; Grabherr et al., 2008; Valko et al., 2012; Priesol et al., 2014). It further aligns with Benson and Brown's (1992) findings on vestibular magnitude estimates, which found that when peak velocity was held constant, participants' magnitude estimates of subjective intensity increased with increasing stimulus frequency.

Most literature on magnitude estimates of speed under visual stimulation use a constant velocity stimulus, rather than a SHA stimulus across multiple frequencies (Brandt et al., 1973; Dichgans & Brandt, 1973; Larish & Flach, 1990). The findings from this study suggest that similar to vestibular stimulation, sensation of speed increases with frequency under visual stimulation. There is clinical relevance in studying perception of visual stimuli that are not delivered at a constant velocity. For example, Butler et al. (2015) found that participants' heading thresholds were more accurate from a raised cosine stimulus, as opposed to a constant velocity stimulus, likely because it better reflected natural head movement.

There was also a significant main effect of peak velocity, where magnitude estimates of speed increased with increasing angular peak velocity (see Figure 8). In pairwise comparisons this reached significance between all peak velocities, except 75 and 90 deg/sec, suggesting that participants did not feel they were going much faster at 90 deg/sec than 75 deg/sec. Brandt and colleagues (1973) found that magnitude estimates of circular vection intensity matched the constant velocity of an optokinetic drum and Larish and Flach (1990) demonstrated a similar effect using a visual display that evoked a sense of forward linear translation. Dichgans and Brandt (1973) also studied magnitude estimation when evoking circular vection from coriolis (i.e., vestibular) and pseudo-coriolis (i.e., visual) stimulation. Their results showed that magnitude estimates of both the coriolis and pseudo-coriolis effect increased with an increase in angular velocity of the chair or drum, which supports this study's findings. Though the stimuli in the present study were not presented at a constant velocity, the findings align with those previously studied and suggest that under vestibular and visual stimulation perception of speed increases with peak velocity. At higher velocities (e.g., 90 to 120 deg/sec), Brandt et al. (1973) observed a saturation of circular vection. Findings from the present study also demonstrated a saturation effect, where magnitude estimates of speed were not significantly different between 75 and 90 deg/sec.

In the limited frequency range we assessed (0.08-0.32 Hz), magnitude estimates of speed were comparable between visual stimulation and vestibular stimulation. This finding is expected, given our understanding that both the vestibular and optokinetic systems are sensitive from .01 Hz to 1 Hz. Future studies may wish to investigate whether there is a decoupling of the speed magnitude estimates between vestibular and visual stimuli at frequencies where the systems are not equally sensitive.

Spatial Orientation Magnitude Estimation

A repeated measures ANOVA was completed to determine the effect of modality, frequency, and peak velocity on the participants' magnitude estimates of spatial orientation. There were significant main effects of modality, frequency, and peak velocity on magnitude estimates of spatial orientation. There were also significant interactions between modality and frequency, modality and peak velocity, and frequency and peak velocity.

As frequency increased, the angular distance that participants moved (or felt they moved) decreased in each modality (see Figure 10). In a single-cycle SHA stimulus, the frequency affects the length of time the chair is moving, where higher frequencies create shorter stimulus durations. If peak velocity is held constant, a shorter stimulus duration means that the rotary chair or video under VR will reach a shorter angular distance. It is therefore expected that participants felt the chair or video turned a shorter distance at higher frequencies, and supports what we know about SHA stimulation.

The repeated measures ANOVA also revealed a significant main effect of peak velocity, where participants' magnitude estimates of spatial orientation increased with peak velocity (see Figure 11). While frequency affects the stimulus duration, peak velocity affects the acceleration rate, where higher peak velocities require faster accelerations. Because the chair (or video of the chair) will turn farther in a given amount of time when under greater acceleration, participants' sensed further angular distance as peak velocity grew. This effect of peak velocity was true under both visual and vestibular stimulation.

Unlike perception of speed, perception of spatial orientation was significantly affected by modality. Participants' magnitude estimates of spatial orientation were consistently smaller under visual stimulation compared to vestibular stimulation. Previous research has found similar effects, where participants underestimated distance traveled under visual stimulation. Frenz and Lappe (2005) found that participants underestimated linear distance traveled for three separate visual stimuli. Sun et al. (2004) found that when optic flow and vestibular information were presented together, magnitude estimation of perceived distance was underestimated compared to vestibular-only conditions. Harris et al. (2000) found similar underestimations of distance traveled from visual optic flow patterns compared to a target presented through physical vestibular movement. They found that when the target was presented visually, participants were quite accurate at estimating the distance they traveled under visual stimulation. The previous studies mentioned all used forward linear translation for their motion profiles, so the findings from this study suggest that this underestimation during visual stimulation also extends to angular motion.

This study's findings revealed significant interactions between modality and frequency, modality and peak velocity, and frequency and peak velocity. This interaction is not surprising, given our understanding of how frequency and peak velocity interact to affect displacement in a SHA stimulus. The maximum displacement of the chair, or the video taken from the chair, is a direct result of the combination of frequency and peak velocity, which is likely driving this interaction.

The present study also investigated perceived spatial orientation through spatial orientation error, where negative error indicates that the participant underestimated their spatial orientation and positive error indicates they overestimated. Anson et al. (2021) analyzed perceived spatial orientation similarly–they calculated their error by subtracting perceived angle from the true angle the chair turned. That study found that under longer angular distance, participants were less accurate (i.e., their spatial orientation error was larger). In that study, participants were only exposed to vestibular stimulation. The present study demonstrates that even at long angular distances, perception of spatial orientation under vestibular stimulation is very accurate, as demonstrated by the vestibular line of best fit being very similar to the line of equality in Figure 13. This discrepancy may be explained by differences in stimuli between that study and the present study. Anson et al. (2021) used manually driven whole body rotations on a swivel chair, where the examiners physically turned the chair an approximated amount of time depending on the distance they turned the chair. This study used a mechanical rotational chair, which applied uniform SHA rotations.

Though Anson et al. (2021) only exposed participants to vestibular stimulation, their finding that participants were less accurate at longer angular distances did align with the present study's *visual* stimulation findings. In Figure 13, the slope of the line of best fit for the visual modality ($y = .73x - 7.82$) is shallower than both the vestibular slope ($y = .93x + 7.90$) and the line of equality ($y = x$), indicating that as angular distance increases, the participants' magnitude estimates will increasingly underestimate true spatial orientation. This finding is also demonstrated by the average spatial orientation error continuing to get more negative as true spatial orientation increases (see Figure 14).

B. Feasibility of Virtual Reality as an Optokinetic Stimulus

Participants were significantly less accurate at estimating the distance they traveled under visual stimulation compared to vestibular stimulation. This is likely because visual cues were taken out of the video displayed under VR, primarily stimulating the optokinetic system. While individuals use visual information for spatial orientation routinely (e.g., optic flow), it is rare that the visual information is similar to the visual cues presented in this study. Whereas optic flow in everyday life comes in the form of distinct landmarks (e.g., specific buildings, signs, people, etc.), there were no distinct landmarks in this study, but rather optic flow *patterns*—vertical stripe*s* overlaid on a distorted video. The lack of visual landmarks may have contributed to the underestimation of spatial orientation in the visual modality.

Interestingly, creating a more immersive, realistic stimulus may have also contributed to the spatial orientation error in the visual modality. Though creating a more realistic visual stimulus allows participants to effectively experience motion intensity, it may actually inhibit their perception of spatial orientation. This is supported by previous findings by Frenz and Lappe (2005), who used three different visual stimuli to induce a sense of forward motion in their participants. They found that the most *realistic* visual scene (i.e., a virtual representation of the ground with a horizon) created the most amount of error in perceived distance traveled. This has implications for visual stimulation under virtual reality, which creates a much more realistic visual stimulus. Though the video under VR was distorted in the present study, it was still a more realistic visual scene than what would be projected on a light bar, for example.

Despite the inaccurate perception of spatial orientation under VR, the results of the present study indicate that an effective optokinetic stimulus for motion perception is feasible with a virtual reality stimulus. Magnitude estimates of speed were not significantly impacted by the modality in which the stimulation was delivered. In other words, the sensation of speed or intensity created under VR goggles effectively mimicked that created under true vestibular stimulation. For both modalities, perception of speed increased as peak velocity and frequency increased, indicating that the optokinetic stimulus created under VR is not only mimicking a vestibular stimulus, but is also being scaled similarly to a vestibular stimulus as intensity grows. Furthermore, the higher FOV provided by VR goggles stimulates the optokinetic system more heavily compared to other OKN stimuli (e.g., light bars), which primarily stimulate the smooth pursuit system. The underestimation of spatial orientation does not necessarily affect VR as an optokinetic stimulus, since the current method of eliciting OKN does not employ any kind of distance measurement. Rather, it assesses the slow phase velocity of the OKN, whose perceptual equivalent is speed or intensity.

Conclusions

1. At frequencies from 0.08 to 0.32 Hz, both vestibular and visual modalities provide adequate cues for motion sensitivity
2. Virtual Reality can be used as an OKN stimulus to assess motion perception (specifically speed/intensity)

Future Directions

Future studies may investigate a wider range of stimulus frequencies to test if perception of speed decouples at higher or lower frequency ranges. The present study only studied a limited frequency range where both systems are sensitive. Another area of future investigation will be to compare suprathreshold magnitude estimates to measures of physiology (i.e., the VOR or OKN).

References

Anson, E., Ehrenburg, M. R., Simonsick, E. M., & Agrawal, Y. (2021). Association between vestibular function and rotational spatial orientation perception in older adults. *Journal of Vestibular Research*, *31*(6), 469–478. https://doi.org/10.3233/VES-201582

Benson, A. J., & Brown, S. F. (1992). Perception of liminal and supraliminal whole-body angular motion. In A. Berthoz, W. Graf, & P. P. Vidal (Eds.), *The Head-neck sensory motor system*. Oxford University Press.

Benson, A. J., Hutt, E. C. B., & Brown, S. F. (1989). Thresholds for the perception of whole body angular movement about a vertical axis. *Avation, Space, and Environmental Medicine*, *60*(3), 205–213.

Benson, A. J., Spencer, M. B., & Stott, J. R. (1986). Thresholds for the detection of the direction of whole-body, linear movement in the horizontal plane. *Aviation, Space, and Environmental Medicine, 57*(11), 1088–1096. [Abstract].

Brandt, T., Dichgans, J., & Koenig, E. (1973). Differential effects of ventral versus peripheral vision on egocentric and exocentric motion perception. *Experimental Brain Research*, *16*, 476–491. https://doi.org/10.1007/BF00234474

Butler, J. S., Campos, J. L., & Bülthoff, H. H. (2015). Optimal visual–vestibular integration under conditions of conflicting intersensory motion profiles. *Experimental Brain Research*, *233*(2), 587–597. https://doi.org/10.1007/s00221-014-4136-1

Chang, N.-Y. N., Hiss, M. M., Sanders, M. C., Olomu, O. U., MacNeilage, P. R., Uchanski, R. M., & Hullar, T. E. (2014). Vestibular Perception and the Vestibulo-Ocular Reflex in Young and Older Adults. *Ear & Hearing*, *35*(5), 565–570. https://doi.org/10.1097/AUD.0000000000000052

Cohen, H., & Keshner, E. A. (1989). Current Concepts of the Vestibular System Reviewed: 2. Visual/Vestibular Interaction and Spatial Orientation. *The American Journal of Occupational Therapy*, *43*(5), 331–338. https://doi.org/10.5014/ajot.43.5.331

Crowell, J. A., & Banks, M. S. (1993). Perceiving heading with different retinal regions and types of optic flow. *Perception & Psychophysics*, *53*(3), 325–337. https://doi.org/10.3758/BF03205187

Dichgans, J., & Brandt, T. (1978). Visual-Vestibular Interaction: Effects on Self-Motion Perception and Postural Control. In R. Held, H. W. Leibowitz, & H.-L. Teuber (Eds.), *Perception* (pp. 755–804). Springer Berlin Heidelberg. https://doi.org/10.1007/978-3-642-46354-9_25

Dichgans, J., & Brandt, Th. (1973). Optokinetic Motion Sickness And Pseudo-Coriolis Effects Induced By Moving Visual Stimuli. *Acta Oto-Laryngologica*, *76*(1–6), 339–348. https://doi.org/10.3109/00016487309121519

Diener, H. C., Wist, E. R., Dichgans, J., & Brandt, T. (1976). The spatial frequency effect on perceived velocity. *Vision Research*, *16*(2), 169-IN7.

Dieterich, M., & Brandt, T. (2018). Global orientation in space and the lateralization of brain functions. *Current opinion in neurology*, *31*(1), 96-104.

Frenz, H., & Lappe, M. (2005). Absolute travel distance from optic flow. *Vision research*, *45*(13), 1679-1692. https://doi.org/10.1016/j.visres.2004.12.019

Gelfand, S. A. (2010). *Hearing: An introduction to Psychological and Physiological acoustics* (5th ed.). Informa UK.

Grabherr, L., Nicoucar, K., Mast, F. W., & Merfeld, D. M. (2008). Vestibular thresholds for yaw rotation about an earth-vertical axis as a function of frequency. *Experimental Brain Research*, *186*(4), 677–681. https://doi.org/10.1007/s00221-008-1350-8

Harris, L. R., Jenkin, M., & Zikovitz, D. C. (2000). Visual and non-visual cues in the perception of linear self motion. *Experimental Brain Research*, *135*(1), 12–21. https://doi.org/10.1007/s002210000504

Henn, V., Young, L. R., & Finley, C. (1974). Vestibular nucleus units in alert monkeys are also influenced by moving visual fields. *Brain Research*, *71*(1), 144–149. https://doi.org/10.1016/0006-8993(74)90198-X

Karmali, F., Lim, K., & Merfeld, D. M. (2014). Visual and vestibular perceptual thresholds each demonstrate better precision at specific frequencies and also exhibit optimal integration. *Journal of Neurophysiology*, *111*, 2393–2403. https://doi.org/10.1152/jn.00332.2013

Keshavarz B, Hettinger LJ, Kennedy RS, Campos JL (2014) Demonstrating the Potential for Dynamic Auditory Stimulation to Contribute to Motion Sickness. *PLoS ONE,* 9(7). https://doi.org/10.1371/journal.pone.0101016

Keshner, E. A., & Kenyon, R. V. (2009). Postural and spatial orientation driven by virtual reality. *Studies in health technology and informatics*, *145*, 209. https://doi.org/10.3233/978-1-60750-018-6-209

Kim, J., & Khuu, S. (2014). A new spin on vection in depth. *Journal of Vision*, *14*(5), 5–5. https://doi.org/10.1167/14.5.5

Kim, J., & Palmisano, S. (2008). Effects of active and passive viewpoint jitter on vection in depth. *Brain Research Bulletin*, *77*(6), 335–342. https://doi.org/10.1016/j.brainresbull.2008.09.011

Kirollos, R., & Herdman, C. M. (2021). Measuring circular vection speed in a virtual reality headset. *Displays*, *69*, 102049.https://doi.org/10.1016/j.displa.2021.102049

Larish, J. F., & Flach, J. M. (1990). Sources of optical information useful for perception of speed of rectilinear self-motion. *Journal of Experimental Psychology: Human Perception and Performance*, *16*(2), 295–302. https://doi.org/10.1037/0096-1523.16.2.295

Leigh, R. J., & Zee, D. S. (2015). *The neurology of eye movements*. Contemporary Neurology.

Lewis, R. F., Priesol, A. J., Nicoucar, K., Lim, K., & Merfeld, D. M. (2011). Dynamic tilt thresholds are reduced in vestibular migraine. *Journal of Vestibular Research*, *21*(6), 323–330. https://doi.org/10.3233/VES-2011-0422

Merfeld, D. M., Park, S., Gianna-Poulin, C., Black, F. O., & Wood, S. (2005). Vestibular Perception and Action Employ Qualitatively Different Mechanisms. I. Frequency Response of VOR and Perceptual Responses During Translation and Tilt. *Journal of Neurophysiology*, *94*(1), 186–198. https://doi.org/10.1152/jn.00904.2004

Mergner, T., Siebold, C., Schweigart, G., & Becker, W. (1991). Human perception of horizontal trunk and head rotation in space during vestibular and neck stimulation. *Experimental brain research*, *85*(2), 389-404.

Niehorster, D. C. (2021). Optic Flow: A History. *I-Perception*, *12*(6), 204166952110557. https://doi.org/10.1177/20416695211055766

Patterson, F., & York, Y. (2009). Vection and motion thresholds as a function of contrast. Naval Aerospace Medical Research Lab: Pensacola, FL.

Piker, E. G., & Jacobson, G. P. (2014). Self-Report Symptoms Differ Between Younger and Older Dizzy Patients. *Otology & Neurotology*, *35*(5), 873–879. https://doi.org/10.1097/MAO.0000000000000391

Piker, E. G., Jacobson, G. P., Romero, D., Wang, Y., & Smith, K. (2020). The Clinical Significance of the Failure to Perceive Vertigo in the Postcaloric Period Despite a Robust Caloric Response. *American Journal of Audiology*, *29*(1), 50–58. https://doi.org/10.1044/2019_AJA-19-00036

Priesol, A. J., Valko, Y., Merfeld, D. M., & Lewis, R. F. (2014). Motion Perception in Patients with Idiopathic Bilateral Vestibular Hypofunction. *Otolaryngology–Head and Neck Surgery*, *150*(6), 1040–1042. https://doi.org/10.1177/0194599814526557

Shepard, N.T. & Schubert, M.C. (2016). Background and technique of ocular motility testing. In G.P. Jacobson & N.T. Shepard (Ed.), *Balance function assessment and management* (Second Edition). Plural Publishing Inc.

Redlick, F. P., Jenkin, M., & Harris, L. R. (2001). Humans can use optic flow to estimate distance of travel. *Vision Research*, *41*(2), 213–219. https://doi.org/10.1016/S0042-6989(00)00243-1

Robinson, D. (1981). Control of eye movements. In *Handbook of physiology section I: The nervous system volume 2 motor control, parts 1 & 2*. American Physiological Society.

Schweigart, G., Mergner, T., Evdokimidis, I., Morand, S., & Becker, W. (1997). Gaze Stabilization by Optokinetic Reflex (OKR) and Vestibulo-ocular Reflex (VOR) During Active Head Rotation in Man. *Vision Research*, *37*(12), 1643–1652. https://doi.org/10.1016/S0042-6989(96)00315-X

Sun, H.-J., Campos, J. L., Young, M., Chan, G. S. W., & Ellard, C. G. (2004). The Contributions of Static Visual Cues, Nonvisual Cues, and Optic Flow in Distance Estimation. *Perception*, *33*(1), 49–65. https://doi.org/10.1068/p5145

Thilo, K. V., Kleinschmidt, A., & Gresty, M. A. (2003). Perception of Self-Motion From Peripheral Optokinetic Stimulation Suppresses Visual Evoked Responses to Central Stimuli. *Journal of Neurophysiology*, *90*(2), 723–730. https://doi.org/10.1152/jn.00880.2002

Valko, Y., Lewis, R. F., Priesol, A. J., & Merfeld, D. M. (2012). Vestibular Labyrinth Contributions to Human Whole-Body Motion Discrimination. *Journal of Neuroscience*, *32*(39), 13537–13542. https://doi.org/10.1523/JNEUROSCI.2157-12.2012

van den Berg, A. V. (1992). Robustness of perception of heading from optic flow. *Vision Research*, *32*(7), 1285–1296. https://doi.org/10.1016/0042-6989(92)90223-6

Warren, W. H., & Kurtz, K. J. (1992). The role of central and peripheral vision in perceiving the direction of self-motion. *Perception & Psychophysics*, *51*(5), 443–454. https://doi.org/10.3758/BF03211640

Warren, W. H., Morris, M. W., & Kalish, M. (1988). Perception of translational heading from optical flow. *Journal of Experimental Psychology: Human Perception and Performance*, *14*(4), 646–660. https://doi.org/10.1037/0096-1523.14.4.646

Wong, A. (2008). *Eye movement disorders*. Oxford University Press.

Zalewski, C. K. (2018). *Rotational vestibular assessment*. Plural Publishing.