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The Relationship Between the Vestibular Ocular Reflex and Vestibular Perception in Young Healthy Adults

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Abstract

Vestibular impairments are often identified through measures of vestibular reflexes such as the vestibulo-ocular reflex (VOR). However, in clinical practice measures of the VOR do not always correlate with the patient's reported symptoms. In contrast to physiologic measures like the VOR, psychophysical methods can be used to assess a person's perception of movement. Previous psychophysics research shows that perceptual thresholds of angular motion do not correlate with VOR measures, but this has not been assessed at suprathreshold levels. The purpose of this study was to assess whether vestibular reflexive responses (i.e., VOR) were correlated to the patient's perception of movement at suprathreshold levels of angular motion in the rotary chair. We evaluated 35 young healthy adults using sinusoidal harmonic acceleration with a rotary chair under 12 different stimulus conditions that varied by frequency and peak velocity at levels well above perceptual threshold. Participants provided magnitude estimates of speed using a visual analog scale. Maximum slow phase velocity (mSPV) of the eyes was used as a measure of the VOR as well as the more frequently used clinical measure of VOR gain (ratio of mSPV to velocity of the chair). Both measures of physiology were recorded simultaneously with the magnitude estimates. Results showed a statically significant correlation (r = 0.582) between magnitude estimates of speed and mSPV and no significant correlation between magnitude estimates and VOR gain. Overall, perception of suprathreshold vestibular stimuli does not correlate with the clinically used variable of VOR gain, but it does correlate with the mSPV in young, healthy participants.

Introduction

I. Vestibular Testing

The gold-standard of vestibular assessment are measures of physiologic reflexes including the vestibulo-ocular reflex (VOR) and the vestibulospinal reflex (VSR). These reflexes can be measured with clinically available tests including calorics, video head impulse test, rotational testing using the rotary chair, and vestibular evoked myogenic potentials. In the current study, we measured the VOR using the rotary chair.

II. Rotational Testing

Rotary chair testing in the yaw axis can assess the function of the horizontal semicircular canals. In a rotary chair test the participant sits in the chair with electrodes around the eyes or with video-oculography (VOG) goggles on to record the VOR. The chair is then rotated, with the most common clinical stimulus being sinusoidal harmonic acceleration at frequencies ranging between 0.01 - 0.64 Hz with a peak velocity between 50-60 degrees per second. This physiologic movement elicits a VOR response in the normal functioning vestibular system. The corresponding eye movements of the VOR are then tracked and measured.

There are specific aspects of the VOR that are determined to assess the function of the vestibular system. VOR gain is the ratio of the peak slow phase eye velocity to the peak velocity of the head itself which has been strapped to the rotary chair. The closer the eye movement is to matching the velocity of the head movement, the better. Perfect gain would be 1.0 meaning that the velocity of the eye movement exactly matched that of the head movement.

The next characteristic of VOR that we measure in the rotary chair is phase. Phase is a measure of timing and is the degree to which the eye movement is in opposite phase with that of the head movement. In a normally functioning system, the eye movement will lead the head movement during sinusoidal harmonic accelerations in the rotary chair by an expected amount depending on the stimulus frequency. The eye movement and head movement are perfectly 180 degrees out of phase with one another only in high frequency movements. Phase leads, the degree to which the eye movement leads the head movement, that are too large reflect a problem with the vestibular system, as phase is a sensitive measure of peripheral vestibular function.

The final portion of the VOR that is assessed with the rotary chair is asymmetry. Asymmetry is a measure of gain when rotating to the right relative to gain when rotating to the left. In the case of a peripheral loss the functioning of one side of the system may be drastically lower than the other, and during dynamic movement there may be gain asymmetries if central vestibular compensation is not complete and there is any spontaneous nystagmus present.

III. Reflex Measurements vs. Vestibular Perception

Vestibular reflex responses, such as the VOR, and patient’s vestibular percepts, such as self-reported symptoms of dizziness or vertigo, do not always align. Piker and Jacobson (2014) assess self-reported vestibular percepts in two categories of dizzy patients: adults (18-64) and older adults (65-91). Reports of true vertigo were four times more likely in the adult group than the older adult group, even though 9% of the older adult group demonstrated BPPV, a disorder known to cause symptoms of vertigo. In contrast, older adults were more likely to report imbalance and unsteadiness, regardless of their physiologic (i.e., VOR-based) findings. Overall results suggested that in a clinical population, vestibular perception, as measured by self-report symptoms, vary by age, and cannot be predicted by diagnostic tests of the VOR.

Vestibular perception in patients measured by the binary yes or no (i.e., do you feel movement or not) also differs by age and cannot be predicted by the VOR. Piker, Jacobson, Romero, Wang, and Smith (2019) assessed motion perception in patients who demonstrated normal VOR function. They divided the patients into groups based on whether they felt motion during caloric stimulation: motion perception and absent motion perception. The VOR, elicited during the caloric test, was normal for all participants yet older adults were more likely to not perceive motion. Further, there were significant group mean differences in a measure of visuospatial working memory and postural stability, with those in the absent motion perception group performing worse. These participants tended to fail on condition five of computerized dynamic posturography which is intended to isolate the vestibular system response from the visual and somatosensory system. So, although diagnostic tests of the peripheral vestibular system were normal, those with absent motion perception tended to perform more poorly on the test designed to tax the vestibular system.

IV. Measurements of Vestibular Perception

Currently, there is not a clinical measurement for vestibular perception, although translational labs have studied perception through measures of psychophysics. Psychophysics is the study of the relationship between stimulus, in the physical domain, and sensation, in the psychological domain. Vestibular psychophysical testing can be used to quantify vestibular perception (i.e., sensation) in response to motion (i.e., stimulus). Most of the work in this area studied perceptual thresholds obtained through detection or discrimination measures.

V. Perceptual Thresholds

Perceptual detection thresholds are designed to determine the smallest vestibular stimulus that a person can detect. Realistically, this is very difficult to do as sensations of vibration are hard to eliminate. Alternatively, many measure what is called direction-recognition thresholds which is a form of perceptual discrimination. Perceptual discrimination thresholds are the smallest difference between two stimuli that a participant can perceive. For example, Grabherr, Nicoucar, Mast and Merfeld (2008) measured vestibular detection thresholds for yaw rotations at several frequencies between 0.05 – 5 Hz. Participants reported whether they perceived rotation to the left or right, resulting in a series of mean yaw rotational velocity thresholds as a function of frequency plotted in what they termed a “vestibulogram”. Depending on the frequency, thresholds for yaw rotation were between 2.8 deg/s and 0.4 deg/s. Thresholds were highest in the low frequencies, with thresholds steadily increasing at 0.2 Hz and below, and plateaued at 0.5 Hz and above. Additionally, Rey et al. (2016), used similar methods but expanded to assess roll tilts in addition to yaw rotation, and determined that vestibular perceptual thresholds begin to decline after the age of 40 years.

Chang et al. (2014) measured both detection and discrimination thresholds in the yaw axis using a rotary chair. For their discrimination thresholds, they utilized sinusoidal rotations at a frequency of 0.5 Hz with a reference stimulus of 60 deg/s. Participants were presented with a pair of stimuli, the reference stimulus and another stimulus that differed in velocity by either 10 or 15 deg/s and participants chose which stimulus was faster. A “three-down one-up” adaptive staircase paradigm was used to determine the detection threshold. The mean discrimination thresholds for the younger adult group was 4.83 deg/s and for the older adult group was 4.3 deg/s (no statistically significant differences between age groups).

In addition to discrimination thresholds, Chang et al. (2014) also attempted to examine correlations between their perceptual threshold data and the VOR. However, to accomplish this they assessed discrimination thresholds in one test paradigm, and then assessed the VOR with a different stimulus at a different time and compared results. For the VOR, they looked at only gain and phase and found no significant correlations between VOR measures and discrimination thresholds.

Vestibular perceptual thresholds provide valuable information regarding the vestibular system that may not be attainable from measures of the VOR alone. However, there are obstacles to overcome. Perceptual thresholds can be technically difficult to obtain, if assessing in more than the yaw plane they require specialized equipment, and they require a long time to measure (i.e., 20-30 minutes per condition). The focus of perceptual threshold studies seems to be on diagnostic assessments (Kobel et al. 2021), though the specialized equipment and time requirements impede their use clinically. Additionally, outside of a diagnostic tool, perceptual thresholds may not have ecological validity. That is, patients do not report symptoms at threshold levels of movement, but report troubles at larger suprathreshold levels of motion.

VI. Magnitude Estimates at Suprathreshold levels of Stimulation

Threshold measures of vestibular stimulation are not adequate to measure the movement that occurs in everyday life as vestibular symptoms are often experienced at suprathreshold levels of motion. Suprathreshold levels of stimulation are those that occur above a threshold level and can be systematically assessed using psychophysics methods such as magnitude estimates. Additionally, magnitude estimates and measures of the VOR can be obtained simultaneously. For instance, if vestibular stimulation is too low, it will not elicit a measurable VOR response using video-oculography goggles. Magnitude estimates obtained at suprathreshold levels of stimulation overcome this while presenting motion at a stimulation level that may be more akin to patient-reported symptoms.

Benson and Brown (1992) used magnitude estimates, with a nominal scale value of 10, to determine if the subjective scaling of suprathreshold oscillating stimuli was frequency dependent. They varied the oscillating stimulus over the range of 0.05 Hz – 1.5 Hz and determined a similar frequency effect as threshold studies, with increased sensitivity with increases in frequency. Cousins et al. (2013) did not use magnitude estimates but did assess perception at suprathreshold levels of motion using a velocity step-type stimulus (i.e., an initial large velocity movement with a sustained rotation of 60 seconds). They measured perception on groups of patients directly after a unilaterally acute vestibular episode and again after recovery (6-16 weeks later). In their study paradigm, participants were asked to turn a tachometer wheel in proportion to their own perceived rotation. VOR responses were measured simultaneously and included time constants and duration measurements of the VOR (measures specific to their stimulus type). Time constants are how long it takes for the VOR to decline to 37% of its initial value, and during a constant rotation the VOR will decline until an acceleration or deceleration occurs. Their results showed that the VOR and measures of perception were disassociated. Specifically, the VOR was asymmetrically reduced (as expected with a unilateral vestibular lesion) but perception in patients was symmetrically suppressed. The mismatch between suprathreshold responses and the VOR could be the product of the unilateral vestibular impairment or could be a general mismatch between vestibular perception and vestibular reflex measurements.

VII. Purpose of the Study

The purpose of this study is to measure magnitude estimates in response to suprathreshold levels of rotation in the yaw axis and compare those estimates to physiologic measures of the VOR recorded simultaneously. It was hypothesized that measure of magnitude estimates of speed would be positively correlated to VOR gain because the slow phase velocity of the eye movement increases with increasing stimulus intensity.

Methods

I. Participants

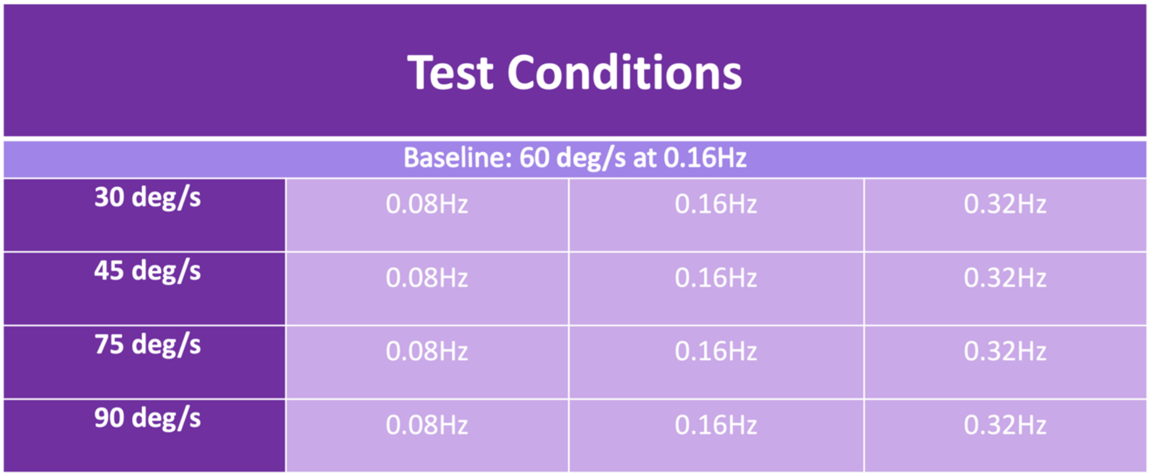
35 young and healthy participants were recruited from the James Madison University student body. Participants were screened for vestibular impairments using a validated case study form (Furman & Cass, 2003). Students were selected on a volunteer basis and were between the ages of 20-28 with a mean age of 22 years old. Exclusion criteria included complaint of dizziness or imbalance, history of ear disease, or individuals taking central suppressant medications which was determined from the above-mentioned case study form.

II. Instrumentation

a. Rotational stimuli

The rotational stimuli were delivered using the Micromedical Technologies System 2000 Rotational Vestibular Chair (Chatham, IL). Preset stimuli were programed into this device to be delivered to participants in a random order. While being run through these conditions, participants were also wearing video-oculography goggles to track eye movements (i.e., the VOR). The VOR data was analyzed for asymmetry, gain, and phase using the Micromedical software.

The 12 stimulus conditions are shown in Table 1. The baseline condition was 0.16 Hz at 60 degrees per second. The test conditions were then varied by frequency and peak velocity. The selected frequencies included 0.08 Hz, 0.16 Hz and 0.32 Hz each presented at a peak velocity of 30, 45, 75, and 90 deg/s. The trials after the baseline condition were varied randomly to negate preference based on order of condition.



Test Conditions

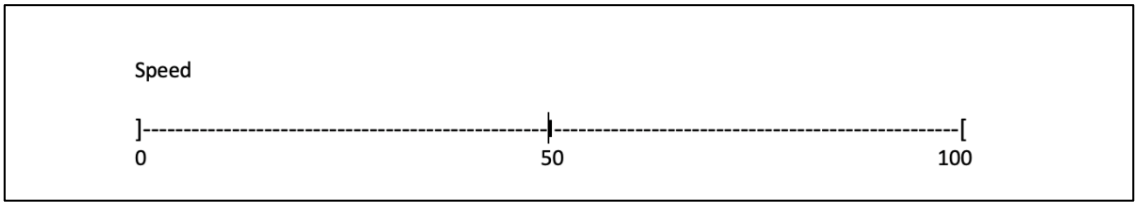
Baseline: 60 deg/s at 0.16Hz

30 deg/s	0.08Hz	0.16Hz	0.32Hz
45 deg/s	0.08Hz	0.16Hz	0.32Hz
75 deg/s	0.08Hz	0.16Hz	0.32Hz
90 deg/s	0.08Hz	0.16Hz	0.32Hz

Table 1: Twelve test conditions varied by four peak velocity conditions (30 deg/s, 45 deg/s, 75 deg/s, 90 deg/s) and three frequency conditions (0.08Hz, 0.16Hz, 0.32Hz).

III. Magnitude Estimation

For each condition the participant provided a magnitude estimate of their perceived speed using the visual analog scale shown in Figure 1. A baseline condition of 0.16Hz at 60 deg/s was assigned “50” with subsequent experimental conditions rated relative to this baseline.



Speed

]--|--[
0 50 100

Figure 1: Data collection sheet containing visual analog scale for magnitude estimates of speed.

IV. Procedure

The participant was set up in the Micromedical Technologies System 2000 Rotational Vestibular Chair and video-oculography goggles were placed. Supra-aural headphones were placed, and white noise presented during the rotations to mask any auditory cues. The white noise was set at a level that the participant could not decern any room noise. During rotations the black visor of the goggles was placed to remove visual cues. The participant was run at the baseline condition of 60 deg/s at 0.16Hz. After the initial run, the black visor was removed, and participants were given the perceptual data sheet to familiarize them with the procedure and demonstrate the baseline condition as the 50% marker.

The conditions were randomized, and the participant was run through each of the 12 conditions. While running the participant through each of the 12 conditions, the video-oculograpy goggles were recording measurement of the participant’s VOR with the black visor down (i.e., in a vision-denied condition). Participants were instructed to keep eyes wide open during the rotations. At the end of each run the participant was asked to fill out the data sheet on their perceived speed of rotation. Then the participant was given time before the next condition was run to reduce any residual vestibular stimulation.

V. VOR Measurements

VOR gain is the ratio of the velocity of eye movement to the velocity of head movements. In a perfect system, the eye movements match the head movements and a gain of 1.0 is obtained. This is expected to occur at frequencies greater than what we presented. VOR gain in healthy populations in this age range is expected to be between ~ .35 - .65, with normative data studies showing very similar gain values (i.e., mean range 0.51 - 0.55) across the frequency range used in this study. (Chan et al., 2016) VOR gain is a measure used clinically to determine the responsiveness of the vestibular system relative to the input stimulus (i.e., the chair or head movement). In the current study, the maximum slow phase velocity of the eye movement (mSPV), or the numerator of the gain calculation, was also tabulated as this should independently increase as acceleration of the chair increases. This measure was chosen as it isolates the physiologic response of the VOR.

Results

Pearson’s correlation coefficients were calculated using IBM SPSS Statistics Software, Version 28 to assess the relationship between VOR gain and magnitude estimates of speed, with a separate analysis between the mSPV of the VOR and magnitude estimates.

Results of VOR gain and magnitude estimates are presented in Figure 2. There was no significant correlation between the two variables ($r = 0.023$, $p = 0.649$).

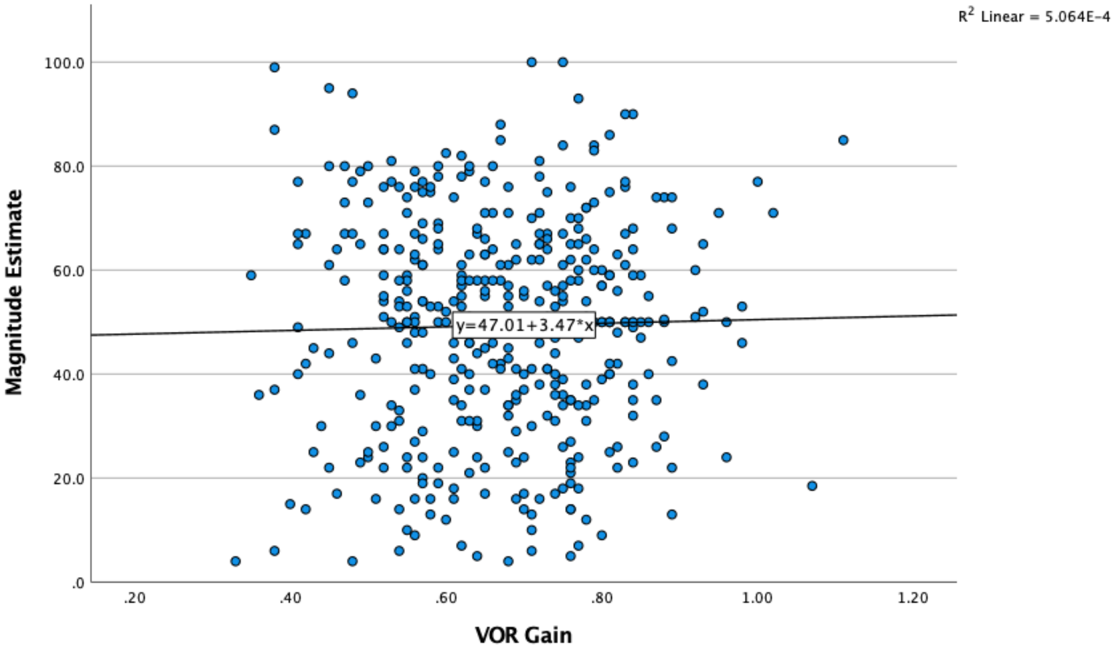


Figure 2: Magnitude estimate of speed as a function of VOR gain presented for each individual participant across all 12 conditions. No significant correlation was observed (r = 0.023, p = 0.649).

Results of the mSPV and magnitude estimates are presented in Figure 4. A moderate and positive significant correlation was observed (r = 0.582, p < .001).

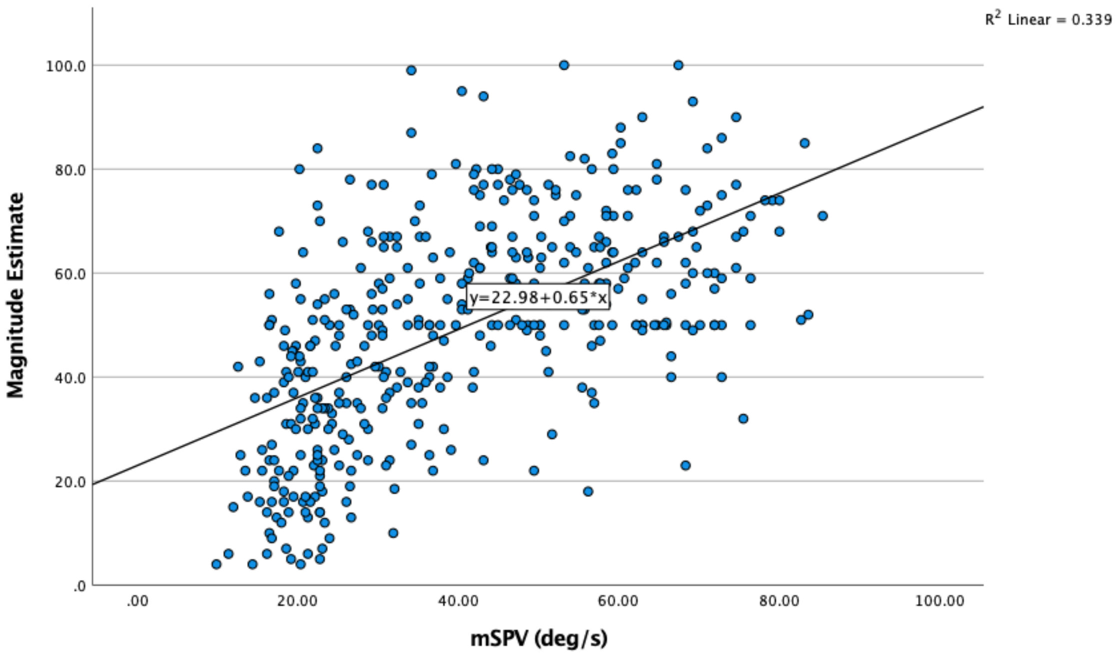


Figure 3: Magnitude estimate of speed as a function of mSPV presented for each individual participant across all 12 conditions. A moderate positive correlation was observed (r = 0.582, p < .001)

To assess whether the association between mSPV and magnitude estimates differed by stimulus frequency, additional correlations were examined for each of the 3 stimulus frequencies. A moderate positive correlation was demonstrated for 0.08 Hz (r = 0.562, p < .001) (Figure 5), 0.16 Hz (r = 0.626, p < .001) (Figure 6), and 0.32 Hz (r = 0.591, p < .001) (Figure 7).

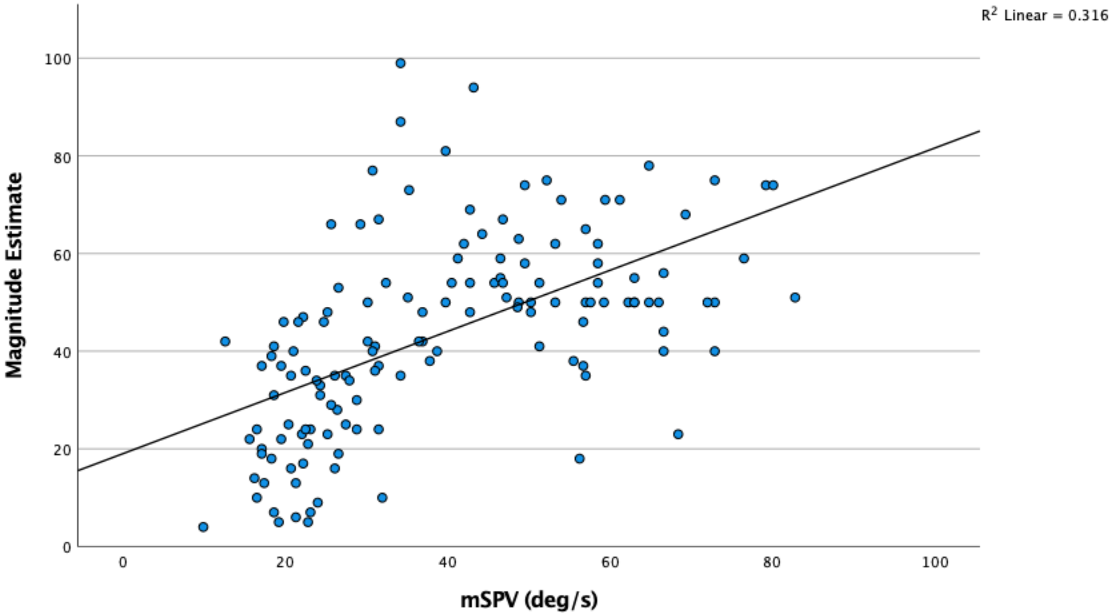


Figure 4: Magnitude estimate of speed as a function of mSPV presented for the 0.08Hz frequency conditions. A moderate positive correlation was observed (r = 0.562, p < .001)

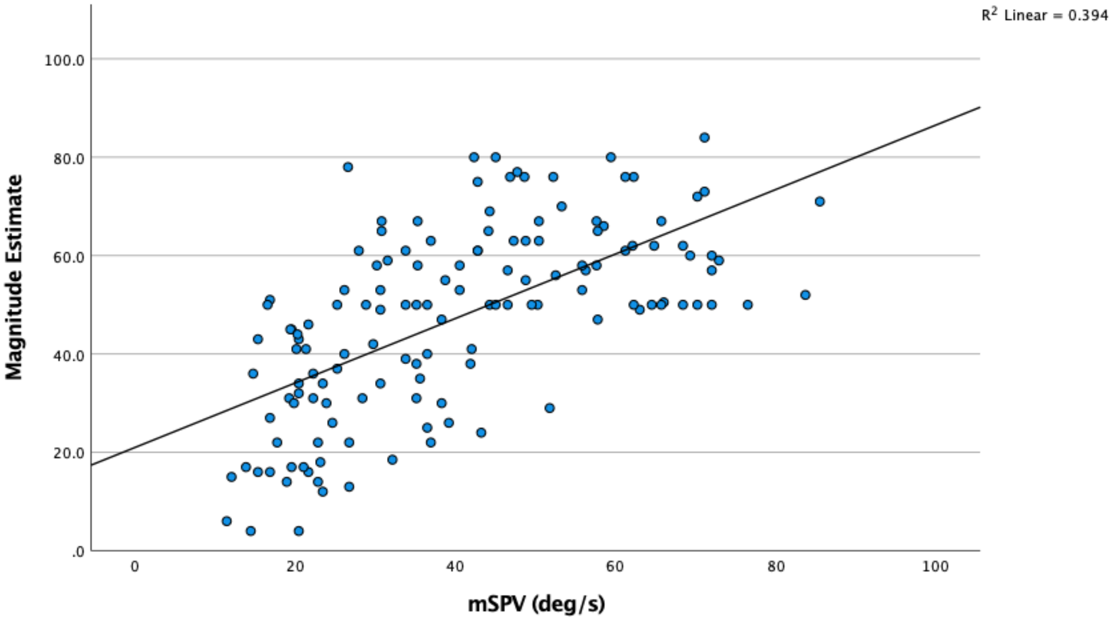


Figure 5: Magnitude estimate of speed as a function of mSPV presented for the 0.16Hz frequency conditions. A moderate positive correlation was observed (r = 0.626, p < .001)

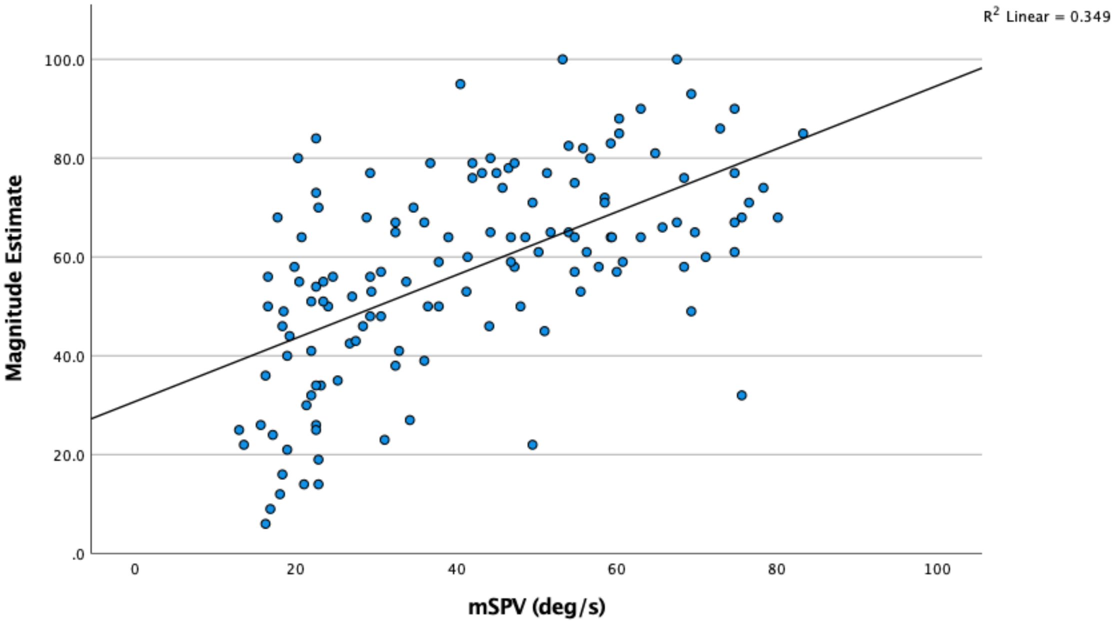


Figure 6: Magnitude estimate of speed as a function of mSPV presented for the 0.32Hz frequency conditions. A moderate positive correlation was observed (r = 0.591, p < .001)

Discussion

The purpose of this study was to characterize the association between VOR reflex measurements and magnitude estimates across 3 stimulus frequencies for rotations in the yaw axis. There was no significant correlation between VOR gain and magnitude estimates of speed. However, there was a significant and moderate positive correlation between the mSPV of the VOR and magnitude estimates. This association was consistent across stimulus frequency.

Gain is a measure of the ratio between eye movement and head movement and is an indication of how the VOR system is functioning. However, in this experiment the participants were young and healthy, so the assumption was that the vestibular system was normally functioning. Figure 2 shows that most participants' gain value fell between 0.6 – 0.8, and all were well within normal limits. In this cohort, it is not surprising that measures of magnitude estimation were not significantly correlated to the measure of VOR gain. Further study using more extended frequencies may yield different results.

In contrast to gain, the mSPV of the VOR was significantly correlated with magnitude estimates of speed. That is, as the chair accelerated the slow phase velocity of the eyes increased as did perception of speed. This relationship was consistent across stimulus frequencies with no frequency yielding a stronger correlation than the others.

Our finding of a moderate statistically significant correlation between the mSPV of the VOR and perception varies from others. Previous studies showed no significant correlation between the VOR and motion perception (Chang et al 2014; Cousins et al. 2013). However, Chang et al. (2014) assessed the VOR separately from discrimination thresholds, and perhaps more importantly the VOR data was obtained using a different stimulus paradigm from the perceptual data. Additionally, they reported VOR gain did not correlate with perception. Our correlation between VOR gain and magnitude estimates, which were recorded simultaneously using the same stimulus, was also not significant and consistent with Chang et al. (2014). The ratio of VOR gain is important diagnostically as we want to determine the velocity of the eye movements relative to the head movement that stimulated the VOR, but when measuring the relationship between perception and physiology it is arguably more sensitive to compare the physiology component, or the mSPV, only. In doing so, a moderate and significant correlation was observed. Additionally, in Cousins et al. (2013) a different stimulus paradigm was used that yielded different VOR measures (time constants and duration) and they assessed patients with unilateral vestibular lesions. In contrast, we used sinusoidal harmonic acceleration and our VOR measures were gain and mSPV. More importantly, we assessed young, healthy adults with normal vestibular systems.

Previous studies concluded that the lack of correlation between perception and physiology was evidence of different central pathways, and that perception provides unique information separate from physiologic measures of the VOR (Chang et al. 2014). However, the current findings of a significant correlation between the mSPV and magnitude estimate of speed does not indicate that reflex measures are the same as measures of vestibular perception. Physiologic reflex pathways like the VOR are brainstem-mediated and perception is a higher-level cortical function with a different pathway. According to Seemungal (2014), the uncoupling or disassociation between the VOR and perception is expected in disordered systems, not in young, healthy systems. This may be why Cousins et al. (2013) observed a disassociation between the VOR and perception as they assessed patients with unilateral vestibular lesions. Additionally, our findings do not suggest the two measures are redundant. In the current study, only a moderate correlation was observed and only 34% of the variance in magnitude estimates are explained by the VOR.

The finding that in young, healthy participants, both magnitude estimates of speed and the mSPV of the VOR increase as the chair accelerates is in line with Ewald's laws. Ewald's first law states eye movements are in the place of the canal stimulated (in this case horizontal SCC). But Ewald's second law states that when the horizontal SCC is stimulated by angular acceleration, endolymph is displaced toward the ampulla in what is called ampullopetal displacement and the firing rate of VOR neurons can be increased with larger ampullopetal stimuli. Because of this, we hypothesized that increases in the angular acceleration across conditions would result in increases in the VOR response (specifically the mSPV) and increases in magnitude estimates of speed. Our results are consistent with greater ampullopetal displacement resulting in a greater VOR magnitude that correlated with greater perception of speed.

I. Limitations

There are several limitations in the current study design that should be addressed. First, this study was performed on young healthy individuals without vestibular pathology or symptoms; thereby limiting the generalizability of the findings to those with vestibular lesions or vestibular symptoms. Second, we used a very narrow stimulus frequency range. Extended frequency results are needed to better delineate the relationship between the VOR and magnitude estimates.

Conclusion

The current study examined the relationship between vestibular magnitude estimates and vestibular ocular reflexes. In young, healthy adults these two measures are moderately and significantly correlated over a narrow frequency range. Notably, vestibular perception is not correlated with VOR gain in this frequency range but is significantly correlated to the maximum slow peak eye velocity of the VOR. More research is required to determine the extent of this correlation along the frequency spectrum, and in aging and pathologic populations.

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