2009

Velocity discrimination of angular motion at different frequencies in individuals with normal vestibular function

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VELOCITY DISCRIMINATION OF ANGULAR MOTION AT DIFFERENT FREQUENCIES IN INDIVIDUALS WITH NORMAL VESTIBULAR FUNCTION

by

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A Capstone Project
submitted in partial fulfillment of the
requirements for the degree of:

Doctor of Audiology

Washington University School of Medicine
Program in Audiology and Communication Sciences

May 21, 2010

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Abstract: The purpose of this study was to evaluate discrimination of angular velocity in individuals with normal vestibular function using a newly developed adaptive psychophysical measure. Vestibular psychophysical testing may complement existing clinical measures in diagnosing and treating patients with imbalance.

Acknowledgements

I would like to thank the following people who helped make this study possible: Timothy Hullar, M.D., for his guidance, support and encouragement in the development and completion of this project; Rosalie Uchanski, Ph.D., for her insight on psychophysical measures; Gammon Earhart, Ph.D., for serving as a second reader; Osarenoma Olomu, M.D., and Robert Mallery, M.D., for their assistance and support in the data collection and analysis; Belinda Sinks, Au.D., for her insights and allowing use of the CAM vestibular clinic for data collection; Valentin Militchin for technical support provided; and to all the study participants for their time and effort.

This Capstone project was supported by:

NIH/NIDCD K08 grant to Timothy Hullar, M.D.

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Abstract

Much is still unknown about the mechanisms of the central vestibular system, particularly in how perception of angular motion is processed. In this study, detection and discrimination of angular velocity in individuals with normal vestibular function was evaluated using a newly developed adaptive psychophysical measure. This measure allowed subjects to perform a two-alternative forced-choice task comparing the intensity of sinusoidal rotations about an earth-vertical axis spanning the range of 40 to 150 degrees per second and at 0.3 and 0.5 Hz. Results indicate that both detection and discrimination thresholds are dependent on frequency, but discrimination thresholds show only a minor dependence on peak velocity. Bilateral peripheral vestibular deficiency correlates with markedly increased thresholds, confirming that the measured thresholds are largely dependent on vestibular input. These results are consistent with the hypothesis that information provided by primary afferent input represents a limiting factor on psychophysical performance of the vestibular system. Vestibular psychophysical testing may complement existing clinical measures in diagnosing and treating patients with imbalance.

Introduction

Dizziness is a common symptom reported in the general population. Nazareth, Yardley, Owen and Luxon (1999) found that at least 4% of patients ages 18-64 years reported persistent and frequent symptoms of dizziness, and at least 3% considered themselves to be "severely incapacitated" over a year after their initial presentation. The prevalence of dizziness in the geriatric population is significantly higher, exceeding 30% (Sloane, Coeytaux, Beck, and Dallara, 2001). In a review of studies examining etiologies of dizziness, Kroenke, Hoffman, and Einstadter (2000) estimated that dizziness was attributed to vestibular causes in at least 50% of cases.

Symptoms of dizziness are difficult for patients to describe and the ability of physicians to diagnose and treat its causes is correspondingly limited. A careful history is critical in evaluating these patients, partly because of the limitations of contemporary laboratory tests of vestibular function. These tests are limited for several reasons. Vestibular testing is relatively imprecise, with wide variability in performance due to factors such as patient inattention or cerumen in the ear canals. In part due to these problems, the test-retest reliability of most vestibular testing is disappointing. Most vestibular tests analyze the responses of the vestibular system only in conditions—such as during caloric irrigations of the external auditory canal—that do not mimic typical stimuli to the system. Some vestibular tests, such as rotatory chair testing, are unable to determine whether a lesion is in the right, left, or both ears. Finally, measurements of vestibular function do not always correspond well to the ability to perform balance-related tasks. This may be because overall balance function requires accurate inputs from several sensory modalities in addition to the vestibular system including vision, audition, and proprioception; the appropriate combination and processing of these modalities; and outputs to appropriate downstream effectors.

Most contemporary tests of patients with imbalance attempt to isolate the contributions of the peripheral vestibular system to downstream vestibular reflexes such as the vestibulo-ocular reflex. This neglects other contributions to central balance-related circuits and ignores other responses guided by those circuits that may contribute to maintaining balance. The only test currently in use that attempts to evaluate these more complicated processes is computerized dynamic posturography, which provides some measure of proprioceptive and visual contributions to balance but only in a relatively qualitative way.

Higher-level cortical processes may also be important in normal balance function and are undoubtedly involved in some patients with imbalance. These cortical processes may be evaluated using standard psychophysical methods. Although introduced over half a century ago and used widely in evaluation of the auditory system, these methods have not previously been used to evaluate vestibular function in patients with complaints of imbalance. Here, we provide psychophysical measurements of the vestibular system in both normal individuals and individuals with vestibular loss. We anticipate they will allow a greater understanding of the various complaints of dizziness presented by patients in the clinical setting, including those related to trauma or aging.

We organize our paper by first providing an overview of familiar auditory testing modalities, to serve as a template for understanding our subsequent description of analogous vestibular testing procedures. We then describe in detail our testing paradigm and results obtained with it. Finally, we discuss the significance of our results, including possible clinical uses for the technique described here in the diagnosis and management of patients with imbalance.

Auditory testing

Physiologic auditory measurements

The most commonly used physiologic measures of the auditory system include otoacoustic emissions (OAEs) and the auditory brainstem response (ABR). OAEs represent vibrations of the tympanic membrane produced by middle ear mechanisms transferring fluid energy of the cochlea through the middle ear, and are measured in the external auditory canal by a sensitive microphone (Katz, 2002). The source of OAEs is believed to be from the "cochlear amplifier," a set of active biologic mechanisms that include outer hair cell (OHC) activity and enhance the response of the basilar membrane (Davis, 1983). OHCs have electromotile properties, which are responsible for mechanical transduction of the stimulus (Gummer, et al., 2002). OAEs are typically categorized as spontaneous or evoked, though generally research and clinical applications have focused on evoked OAEs due to a significant percentage of individuals with normal OHC function who do not exhibit spontaneous OAEs (Katz, 2002). Evoked OAEs include electrically evoked OAEs and stimulus frequency OAEs, which are generally limited to applications in research, and transient evoked OAEs (TEOAEs) and distortion product OAEs (DPOAE), which can also be measured in a clinical setting (Katz, 2002). TEOAEs and DPOAEs can assist the clinician in distinguishing a cochlear lesion from a retrocochlear lesion in the presence of a sensorineural hearing loss.

ABRs assess the integrity of the auditory pathway structures from the spiral ganglion cells of the auditory nerve to the lateral lemniscus fibers leading to the contralateral inferior colliculus of the auditory brainstem (Hall, 2006). The waveform generated by the ABR primarily reflects synchronous activity produced by onset responses of axons in the auditory system (Hall, 2006). The central auditory structures enhance the auditory signal in various manners, such as improving frequency resolution and signal-to-noise ratio and optimizing localization cues (Katz, 2002). ABR responses are used clinically as a neurodiagnostic tool to evaluate retrocochlear function and to estimate hearing sensitivity in infants or other individuals who cannot provide reliable behavioral responses to pure-tone testing.

Behavioral auditory measures: Perception of threshold

In contrast to physiologic measures of hearing, behavioral audiometry relies on a patient's direct participation to complete a psychophysical task. Since its introduction in 1943 by C.C. Bunch, it continues to be the most basic component in an audiometric test battery (Katz, 2002). A sound stimulus (e.g. pure tone or narrowband noise) is delivered via insert earphones, headphones, or a bone oscillator, and presented until threshold is determined by the point where the individual detects the sound 50% of the time. Results from pure-tone measures are plotted on an audiogram, with intensity thresholds as a function of frequencies ranging from 250 Hz to 8000 Hz where most speech sounds occur. Behavioral measures of hearing sensitivity evaluate the integration of peripheral and central auditory structures at frequencies most meaningful in everyday situations.

Behavioral testing is often used in conjunction with physiologic testing to form the most complete evaluation of the auditory system. Though there is a strong correlation between behavioral thresholds and DPOAE amplitudes and thresholds, significant variability in DPOAE amplitudes and thresholds exists across individuals with similar behavioral thresholds. At 4000 Hz, for example, DPOAE thresholds for individuals with a 0 dB HL behavioral threshold can range from 7-40 dB (Gorga, et al.,1993). Similar patterns can be found with ABRs, as individual ABR thresholds can vary significantly from behavioral thresholds despite an apparent strong correlation between the two measures. Gorga, et al. (2006) found in a retrospective study of 140 ears of 77 patients ranging in age from 5 days to 20 years (with 71 of the 77 patients under 5 years of age) that the mean differences between responses from ABR stimuli and behavioral thresholds at identical or similar frequencies were on the order of ±2 dB, but ranging as wide as ±20 dB for some individuals. Nonetheless, DPOAE and ABR thresholds can be used to confirm or refute behavioral testing results that are not fully reliable. Physiologic testing used in conjunction with behavioral measures can provide valuable information in many clinical situations, including cases of possible functional hearing loss, pediatrics, and auditory processing.

Behavioral auditory measures: Suprathreshold perception

A familiar behavioral audiogram indicates the amplitude required for a pure frequency tone to be detected 50% of the time. In contrast to measuring where a signal can be detected, suprathreshold measures examine how an individual processes auditory stimuli at a clearly audible level. A commonly used suprathreshold measurement is the difference limen (DL) or just noticeable difference, which is the smallest perceivable difference between two frequencies or intensities of auditory stimuli. One commonly used method for measuring DLs is a two-alternative forced choice (2AFC) adaptive procedure, in which an observer is required to select one of two possible responses, and the subsequent comparison stimulus presented is determined by whether the response provided was correct (Leek, 2001). DLs that can be measured from auditory stimuli include discrimination thresholds of frequency, intensity, and temporal cues, any of which can indicate an individual's ability to extract components of the signal that provide meaningful information. Frequency, intensity and temporal resolution can affect perception of segmental information (such as periodicity which distinguishes vowels from consonants, and place and manner cues of consonants) or suprasegmental information (such as prosody, stress, and intonation) in speech stimuli (Katz, 2002).

Suprathreshold testing has demonstrated much about the function of the auditory system that is not available from standard detection thresholds. Normal hearing individuals have been shown to have a great differential sensitivity to frequency and sensitivity whereas those with sensorineural hearing loss have decreased discrimination ability. Using a 2AFC procedure, Florentine, Buus, and Mason (1987) found mean DLs for intensity discrimination of 0.25 to 16 kHz pure-tone stimuli in normal hearing observers to vary as a function of frequency and intensity, but overall fall in a narrow range of 0.68 dB SPL to 3.73 dB SPL. For 14 listeners with sensorineural hearing loss, Florentine, et al. (1993) found mean DLs for intensity discrimination at a 1 kHz pure-tone stimulus to vary by configuration of the hearing loss, but overall be higher compared to a control group of six listeners with normal hearing. Freyman and Nelson (1991) found increased frequency DLs between 300 Hz and 8000 Hz for 12 observers with sensorineural hearing loss compared to seven normal hearing individuals. The correlation between these perceptual measures and peripheral hearing sensitivity suggest that frequency and intensity coding deficits can manifest from damage to the cochlea, and the missing information leads to poorer resolution of the auditory signal. Suprathreshold measures can therefore identify specific functional deficits related to the central auditory system, which can aid in adjusting the signal processing in amplification to improve perceived clarity of the auditory signal.

If there is a deficit along the auditory pathway, or in the auditory cortex, an individual may exhibit difficulties with processing one or more components of verbal and/or non-verbal suprathreshold auditory stimuli. Those with suspected central disorders, such as Auditory

Processing Disorder (APD) or Auditory Dys-synchrony (AD), typically demonstrate poor speech understanding as measured through suprathreshold word recognition measures despite normal behavioral audiometric thresholds (Moore, 2006; Vlastarakos, Nikolopoulos, Tavoulari, Papacharalambous, and Korres, 2008). Deficits can occur in different areas of higher-level processing, such as feature extraction or temporal resolution. Suprathreshold assessments such as the Phonemic Synthesis Test, which primarily evaluates the ability to blend individual phonemes (Katz, 2002), and the Random Gap Detection Test, which primarily evaluates an individual's temporal resolution (Roeser, 2000), can identify these specific areas of reduced processing capabilities. Perceptual measures at suprathreshold levels can assist the clinician in developing a more effective treatment plan by isolating areas of higher-level processing in need of improvement, and rehabilitation or habilitation can be tailored to target those skills accordingly.

Vestibular testing

Physiologic vestibular measurements

As with audiologic testing, evaluation of the vestibular system includes physiologic and behavioral testing. Overall vestibular function is primarily quantified by examining the reflexive responses to input from the peripheral vestibular organs. Function of the horizontal semicircular canal is most often tested, although contemporary testing paradigms allow each of the end organs to be evaluated in isolation (Hullar and Minor, 2003). The reflexes that can be measured include the vestibuloocular reflex (VOR), sacculocervical reflex and the vestibulospinal reflex (VSR). A standard clinical test battery evaluating these reflexes, including caloric irrigations, rotatory chair testing, vestibular-evoked myogenic potentials (VEMPs), and computerized dynamic posturography, can identify a deficit in the structures that contribute to the overall response of the physiologic function of the vestibular system.

Understanding these tests requires a basic understanding of the physiology of the vestibular system. The vestibular branch of the eighth cranial nerve encodes the motion stimulus by modulation of the discharge rate of the afferent nerve fibers, and then transmits the information to the vestibular nuclei (Hullar and Minor, 2003). The nerve activates in response to angular head movement as detected by the semicircular canals, which are peripheral end organs of the vestibular system filled with endolymph. The sensation of movement is created by pressure on the crista, a bundle of hair cells located within the ampula near the end of each canal, which results from ampullopetal or ampullofugal endolymph flow (Hullar and Minor, 2003). The direction of flow determines whether the hair cells are excited or inhibited. As the hair cells in the canals of the side ipsilateral to the direction of movement are excited, the respective hair cells in canals on the opposite side are inhibited, which results in asymmetrical neural input

(Egmond, Groen, and Jongkees, 1949). The vestibular nuclei, which are part of the central vestibular system, then send the signal to the oculomotor nuclei, which results in a contraction of the lateral rectus muscle of the eye contralateral to the direction of movement and the medial rectus muscle of the eye ipsilateral to the direction of head movement (Buttner-Ennever, 1992).

Vestibular nuclei integrate information from visual, somatosensory and vestibular inputs. The central vestibular system also includes the cerebellum, which coordinates motor and sensory information. VOR dysfunction can result in nystagmus, an eye beating characterized by fast and slow components (Desmond, 2004). The nystagmus is typically characterized by the direction of the fast component, but the slow component is driven by the VOR and is therefore more physiologically relevant. Deficits of the VOR can also result in oscillopsia, a reduction in visual acuity due to impaired eye movements in relation to head movements.

Vestibular evoked myogenic potential testing primarily evaluates the function of the saccule, which activates a reflexive contraction of the ipsilateral sternocleidomastoid muscle in response to an auditory stimulus of high intensity (Zhou and Cox, 2004). Video-nystagmography encompasses a battery of tests that evaluate reflexive eye movements, and typically includes bithermal caloric irrigation, which tests the integrity of individual horizontal semicircular canals (Fife, et al., 2000). Caloric irrigations stimulate the vestibulo-ocular reflex by direct warming of the afferents and by convective flow of the endolymph through the membranous duct. Rotatory chair testing assesses VOR function across a range of frequencies (Fife, et al., 2000).

Computerized dynamic posturography testing evaluates the contribution of visual, somatosensory, and vestibular inputs to balance function, and also examines vestibulospinal reflex (VSR) function (Black, 2001; Badaracco, Labini, Meli, De Angelis, and Tufarelli, 2007).

The VSR contributes to an individual's ability to maintain posture while standing or ambulating, and involves a short latency response of neck muscle contractions to perturbations (Hullar and Minor, 2003). Vestibular afferents may provide little or no contribution to postural control when the central vestibular system receives accurate visual and somatosensory information; however, when visual and somatosensory cues are compromised or absent, the vestibular system is responsible for preventing involuntary sway while in the upright position (Nashner, Black and Wall, 1982; Horak, Nashner, and Diener, 1990). VSR dysfunction can result in abnormal posture or head tilt.

Behavioral vestibular measures: Perception of threshold

Clinical laboratory measures of the vestibular system can identify deficits related to function of the vestibular reflexes or of the peripheral vestibular organs. However, there exists a subset of individuals who report symptoms of imbalance yet ultimately have normal responses to clinical vestibular testing. It may be possible that impairment in central processing of motion stimuli may contribute to vestibular dysfunction, and behavioral vestibular testing may provide information related to the inputs of central vestibular components.

Almost no recent studies have used behavioral measurements to evaluate vestibular function. One such behavioral measurement is the detection of angular rotations. Clark (1967) reviewed several studies (Groen and Jongkees, 1948; Hallpike, Hood and Byford, 1952; Hallpike and Hood, 1953; Hilding, 1953; deVries and Schierbeek, 1953; Mann and Ray, 1956; Montandon and Russback, 1956; Roggeveen and Nijhoff, 1956) on angular acceleration thresholds in the yaw plane about an earth-vertical axis in humans using a rotatory chair and found results ranging from 0.035 degrees per second^2 to 8.2 degrees per second^2 with a median of approximately 1.0 degrees per second^2. Differences in methodologies, from stimulus duration to method of presentation and response, accounted partially for the significant variations in the thresholds. Variations were also attributed to limitations in precision of stimulus measurements and abrupt transitions from zero velocity to a constant angular acceleration and from a constant angular acceleration to a constant angular velocity, which presented challenges with maintaining consistency in the stimuli used.

Three recent studies have further quantified behavioral responses to detection of angular motion. Benson, Hutt and Brown (1989) obtained detection thresholds of angular velocity about an earth-vertical axis for 30 subjects, 15 males ages 20-49 years (mean = 26.9 years) and 15 females ages 20-60 years (mean = 26.6 years) across a range of frequencies from 0.05 Hz to 1.11 Hz using a cosine trajectory stimulus. Participants were presented stimuli in a forced-choice adaptive procedure, which converged on the 75% point on the psychometric function. Thresholds ranged from 0.54 to 4.13 degrees per second, which were less variable than previous measures. Unlike previous studies, they attempted to control for somatosensory and auditory cues by using padding and white noise. Threshold values for lower frequencies were higher compared to higher frequencies across the frequency range tested. Becker, Jürgens, and Boß (2000) examined the effect of posture on detection of angular motion. There was no significant difference found between standing and sitting detection thresholds.

Grabherr, Nicoucar, Mast, and Merfeld (2008) reported detection thresholds of angular velocity about an earth-vertical axis as a function of frequency in ten healthy subjects using sinusoidal acceleration stimuli, with mean detection thresholds ranging from 0.59 degrees per second at 5 Hz to 2.84 degrees per second at 0.05 Hz. Participants were presented stimuli in a forced-choice adaptive procedure designed to converge on the 79.4% point on the psychometric function. Threshold values for lower frequencies were higher compared to higher frequencies, which is consistent with results obtained by Benson, et al. (1989). In the range of 2 Hz to 5 Hz, a range not achieved by the previous study, the thresholds reached a plateau which Grabherr, et al. (2008) suggested support the theory that the semicircular canals detect angular velocity at more physiologic frequencies rather than angular acceleration. Grabherr, et al. (2008) suggested that these findings could be related to the gain of afferents, which are known to be lower—and presumably provide less available information—at lower frequencies than higher frequencies (Sadeghi, Chacron, Taylor, and Cullen, 2007).

Behavioral vestibular measures: Suprathreshold perception

Discrimination measures may reveal more information related to dynamic balance function than detection thresholds. Most of the current literature has focused on perception of tilt and translation (Angelaki, Wei and Merfeld, 2001; Merfeld, Park, Gianna-Poulin, Black, and Wood, 2005). As most physiologic tests of vestibular function measure semicircular canal responses, psychophysical testing using rotational stimuli can provide a more comprehensive evaluation of how the vestibular system responds to rotational movements.

The present study will evaluate velocity discrimination of sinusoidal rotational stimuli at two different frequencies in individuals with normal vestibular function. We hypothesize that for a given velocity, the discrimination thresholds will improve at higher frequencies. We further expect to find that the discrimination thresholds will remain constant over the range of velocities tested at a particular frequency, as the gain of vestibular afferents has been shown to remain constant across an extended range of angular velocities for a given frequency of rotation (Fernandez and Goldberg, 1971).

Methods

Motion Stimuli

Sinusoidal rotational stimuli were presented at a constant frequency, set to 0.3 Hz or 0.5 Hz. Each stimulus had two distinct periods, one at a standard velocity (60, 100 and 150 degrees per second) and a comparison velocity, always with a higher maximal velocity than the standard. Figure 1 displays a representative stimulus profile. In this example, angular rotation begins and the chair is accelerated to the first peak velocity (40 degrees per second) over one second. The first stimulus, which in this case is the standard velocity, is presented for four seconds. The chair then accelerates or decelerates to the second peak velocity (in this case, accelerates to 45 degrees per second) over one second. The second stimulus is presented for four seconds. The chair is then decelerated to 0 degrees per second and the trial ends. An auditory cue is presented during the stimulus interval to alert the subject to the presence of the stimulus.

The stimulus duration was dependent on the frequency selected. Though each velocity was presented for 2.5 cycles, the total length of one trial for 0.5 Hz was 18 seconds, and the total length of one trial for 0.3 Hz was 30 seconds. The standard and comparison velocities were presented in random order.

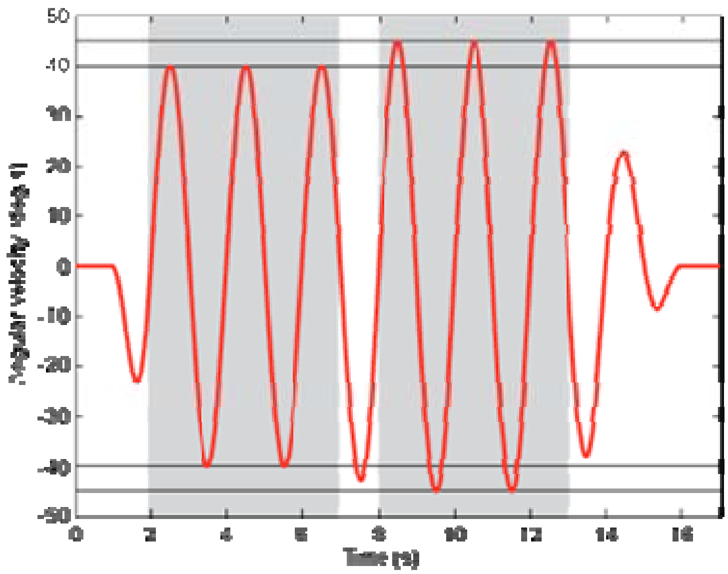

Figure 1. An example of a stimulus profile for one trial at 0.5 Hz. Red tracing indicates head velocity. The observer is to determine which of the two angular velocity stimuli (indicated by the shaded grey areas) is faster.

Velocity storage

Performing psychophysical testing on rotational stimuli is subject to difficulties related to the velocity storage mechanism. This brainstem neural circuit retains information from vestibular neural inputs and gradually discharges over a period of 5-20 seconds (quantified as the time constant of the VOR), which results in an individual perceiving post-rotatory angular motion (Leigh and Zee, 2006). Figure 2 illustrates the potential effect of velocity storage on a 0.5 Hz sinusoidal stimulus with peak velocity at 40 degrees per second and a duration of five seconds. Shown are both the presented signal (in blue) and the estimated signal output (in blue) of the velocity storage mechanism (Maioli, 1988). According to this model, an observer can experience perception of movement for an extended period of time after cessation of the stimulus. The inset demonstrates that this perception can theoretically persist up to 60 seconds or longer after cessation of the stimulus, although the observer may no longer notice its effects as it approaches zero. Additional stimuli presented during this period might have a cumulative effect on velocity storage, potentially affecting the perceived velocity of subsequent stimuli.

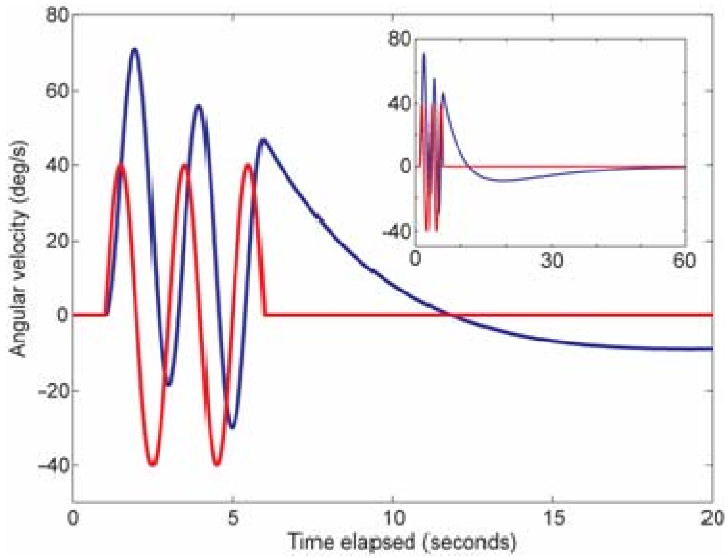

Figure 2. Effect of velocity storage on central vestibular mechanisms. The red line indicates the presented stimulus. The blue line indicates the response after filtering through the velocity storage mechanism. (Mallery, et al., ARO abstract 2009). Inset extends scale to demonstrate extended duration of the effect, whose time constant in normal subjects is 12-20 seconds.

We attempted to eliminate the possible effect of the velocity storage mechanism stimulated during the first rotation interval on the second interval by developing a novel paradigm essentially eliminating the effects of velocity storage. Figure 3 shows our theoretical model for demonstrating the absence of residual velocity storage using our sinusoidal stimulus profile. The red line indicates the actual rotatory chair trajectory, and the blue line indicates the perceived angular motion resulting from velocity storage according to our theoretical model. The perceived stimulus as predicted by the velocity storage model follows the rotational stimulus presented in the shaded regions, and velocity storage returns to zero at the end of the trial. A comparison to Figure 2 shows that it successfully eliminates virtually all of the undesired effects of the velocity storage mechanism.

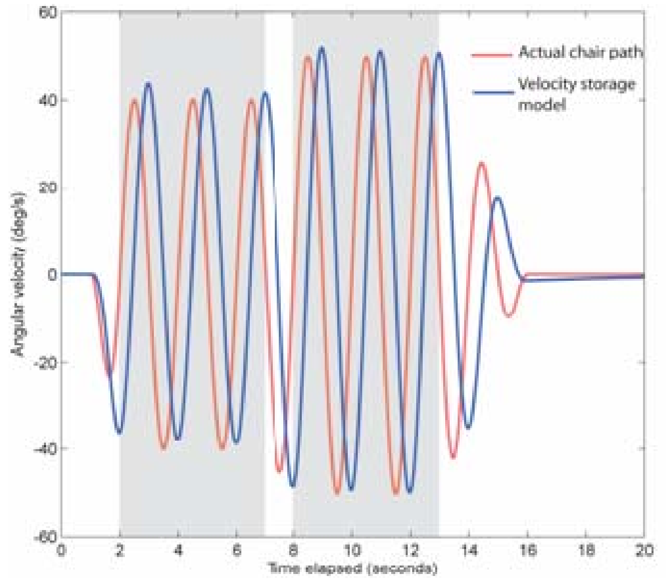

Figure 3. Minimization of velocity storage effect due to design of current paradigm. The red line indicates head movement. The blue line indicates the calculated signal after passing through the velocity storage filter.

Experimental Procedure

For the velocity discrimination test, each participant was seated in a completely dark room and secured with a four-point harness in a commercially used rotatory chair (System 2000, Micromedical Technologies Inc., Chatham, IL) with the head tilted 30 degrees downward to achieve maximal horizontal canal stimulation. Custom-written software in Matlab was used to calculate chair trajectories, and a National Instruments Data Acquisition device (Austin, TX) in conjunction with the Matlab Data Acquisition Toolbox provided input to the chair controller. An adaptive three-down one-up two-alternative forced-choice paradigm was selected, where three correct responses resulted in a decrease in the comparison velocity by one degree closer to threshold, and one incorrect response resulted in an increase of the comparison velocity one degree per second further away from threshold (Leek, 2001). The initial comparison velocity was set at 15 degrees per second above the standard velocity. After 40 trials, the step size was decreased to 0.5 degree per second to establish more precise measurements near threshold. Each run terminated after 14 reversals, with an average of 78 trials per run. The discrimination thresholds were calculated by averaging the last three values where reversals occurred. Figure 4 shows an example of an adaptive staircase paradigm displaying the changes in the level of the comparison velocity by trial number based on the observer's responses. The standard velocity in this example is 60 degrees per second, and the initial comparison velocity is 75 degrees per second.

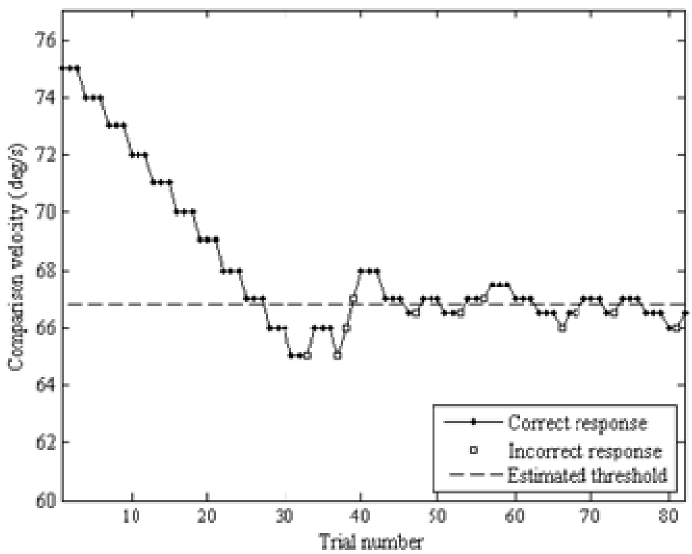

Figure 4. Staircase adaptive paradigm. The filled diamonds indicate correct responses and the open squares indicate incorrect responses. The dashed line indicates the estimated velocity discrimination threshold for the given standard velocity.

Great care was taken to ensure that the contributions of non-vestibular cues were minimized. Each participant wore headphones that delivered Gaussian white noise throughout the duration of the run to minimize auditory cues. Foam padding was placed under the participant's feet and on the sides of the chair, between the participant's knees, and in front of the legs, and behind the participant's head on the headrest to minimize somatosensory cues. The participant was instructed to close his/her eyes during the trials. Verbal instructions were given to each participant prior to starting the testing. An 800 Hz tone was presented from the beginning to the end of each velocity to indicate the stimulus for evaluation. At the end of each trial, the participant reported which rotation was perceived as faster by responding verbally, "one" or "two." Every three trials, the chair light was turned on for 5-10 seconds to help the participant remain alert. The participant was allowed a break between each run, and no more than three runs were performed in a session to control for fatigue.

Participants

Six female participants ages 23-26 years (mean age = 25 years) and one male participant (age = 24 years) with normal vestibular and neurological function volunteered for this study. Participants were recruited from the Central Institute for the Deaf at Washington University School of Medicine in St. Louis, MO, and by referrals. All participants were screened for normal vestibular and neurological function. No spontaneous nystagmus was noted. All denied use of drugs or alcohol the day of the test.

One male participant (age 16 years) with a bilateral profound sensorineural hearing loss and bilateral loss of vestibular function following CMV infection at three years of age served as a control to quantify our ability to eliminate non-vestibular motion cues in the experiment. He had no responses to ice water caloric irrigations bilaterally and no measurable gain on rotatory chair testing. He is a bilateral cochlear implant user and wore his devices during the experimental procedure in order to hear the auditory tone used to cue participants to the segments of sinusoidal rotation.

The Human Studies Committee at Washington University approved all experimental procedures, and participants completed an informed consent process prior to the first session of testing. In the case of our participant with bilateral vestibular hypofunction who was a minor, consent was also obtained from his legal guardian.

Results

If velocity storage remained a confounding factor in our experiments, we expected to find that the participants had an ongoing perception of motion or jerk nystagmus typical of vestibular stimulation following each trial. Neither of these was observed for any of the participants in this study. Any significant contribution of velocity storage would also tend to favor choosing the second choice over the first one when both are equal. To test this, one participant was presented with a total of 420 paired tests with 60 at equal velocities. The total number of responses corresponding to the first velocity is equivalent to the total number of responses corresponding to the second velocity ($p < 0.05$). This finding remained stable over multiple repetitions.

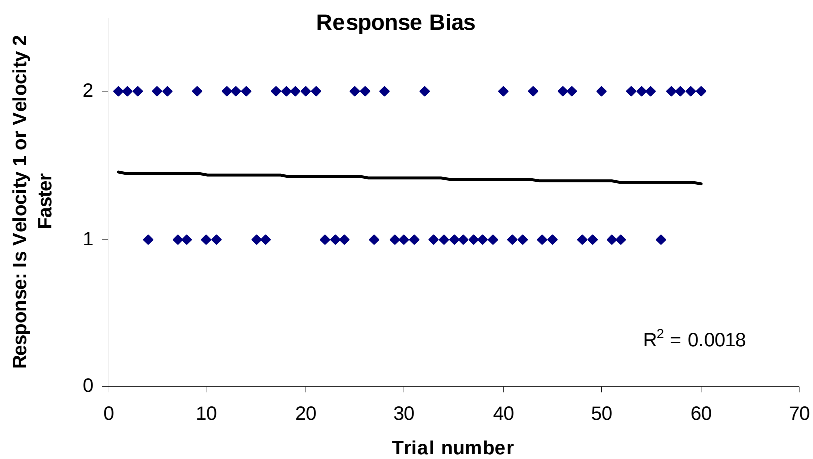

Figure 5. Lack of response bias toward the second choice in a 2AFC task involving rotations.

Individual yaw velocity *detection* thresholds were obtained for one participant. Her detection threshold at 0.3 Hz was 1.47 degrees per second and at 0.5 Hz was 1.10 degrees per second. These were similar to those reported in Grabherr, et al. (2008).

Velocity discrimination thresholds at 60, 100, and 150 degrees per second at 0.3 and 0.5 Hz were obtained for all seven participants and for the participant with bilateral vestibular hypofunction using the paradigm previously described. Results for individual participants are shown in Figure 6. A wide range of responses is present, although the 0.3 Hz thresholds tend to be slightly greater than the 0.5 Hz.

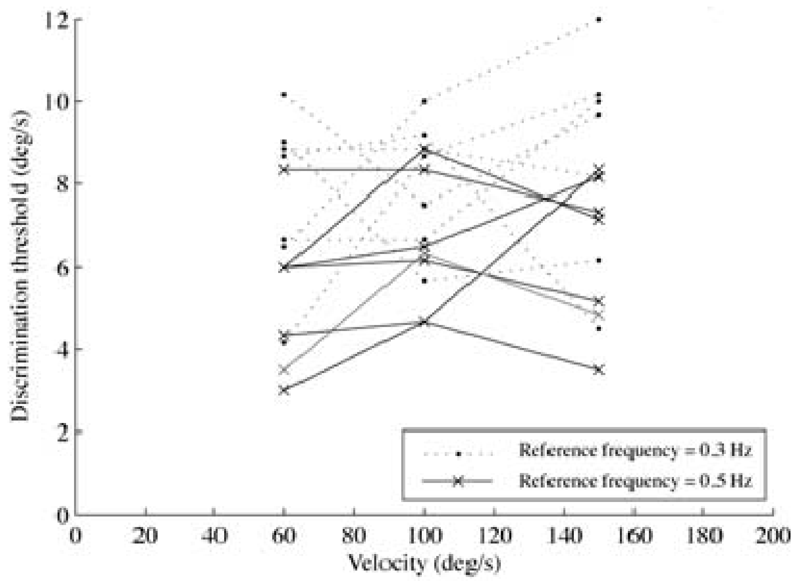

Figure 6. Individual yaw velocity discrimination thresholds for participants with normal vestibular function as a function of velocity.

Grouped data for all participants including the single participant with bilateral vestibular hypofunction are presented in Table 1. There is no statistically significant difference between velocities at each frequency, although at each velocity there is a difference between frequencies. The exceptionally high thresholds for the participant with bilateral vestibular hypofunction (at least four times the mean threshold for the normal participants) confirms that little non-vestibular information was available to the participants.

Table 1 Mean velocity discrimination thresholds for yaw rotations (mean ± standard error of the mean)

		40 deg/sec	60 deg/s	100 deg/s	150 deg/s
Normal participants	**0.3 Hz**		8.31 ± 0.83	7.97 ± 0.62	8.42 ± 1.05
	0.5 Hz		5.61 ± 0.75	6.53 ± 0.66	6.67 ± 0.76
Control participant	**0.5 Hz**	35.0		33.7	

Results for yaw discrimination thresholds at each frequency and velocity are plotted individually for each participant in Figure 7. Almost without exception, participants performed better (lower threshold) at 0.5 Hz than at 0.3 Hz at all velocities tested. The sole inconsistency was participant #1, who did slightly poorer at 0.5 Hz than 0.3 Hz at 150 degrees per second. Paired one-tail t-tests comparing thresholds obtained at 0.3 Hz and 0.5 Hz for each velocity revealed these differences to be statistically significant ($p < 0.05$).

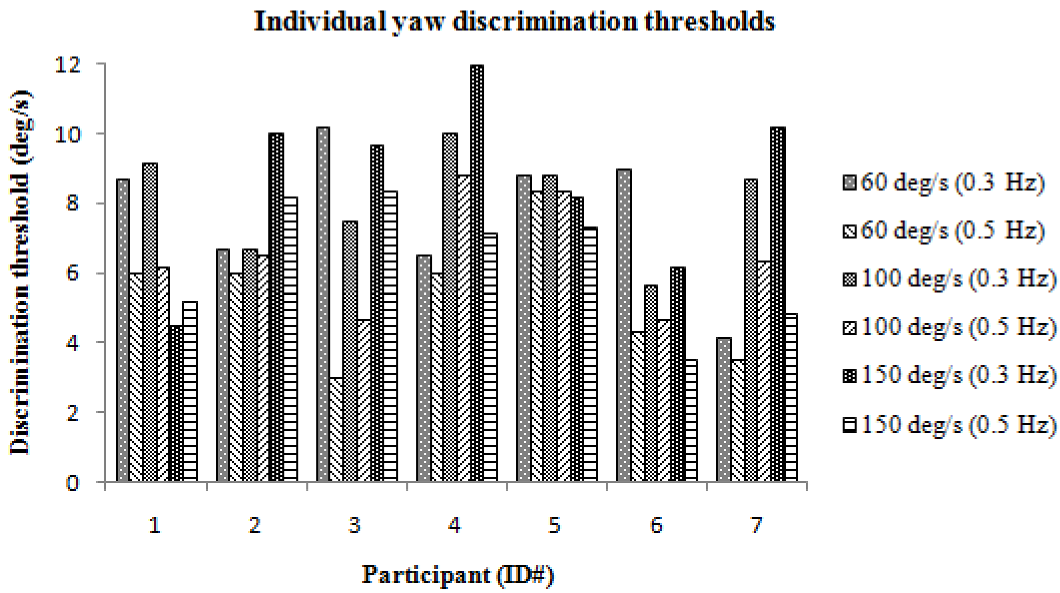

Figure 7. Individual yaw velocity discrimination thresholds for individual participants with normal vestibular function. Thresholds are categorized by standard velocity and reference frequency.

The dependence of threshold on stimulus velocity was tested for the 0.3 Hz condition and for the 0.5 Hz condition. A fit to the data at 0.5 Hz reveals a line equation of $y = 0.01073x + 4.899$ (95% CI of intercept: -6.716, 16.49; 95% CI of slope: -0.09057, 0.112; adjusted $r^2 = 0.2885$). A fit to the data at 0.3 Hz reveals a line equation of $y = 0.01067x + 7.054$ (95% CI of intercept: 5.995, 8.113; 95% CI of slope: 0.001423, 0.01991; adjusted $r^2 = 0.9907$).

Discussion

Several methods are currently available for measuring balance function, but each has specific limitations. In particular, most techniques measure only vestibular reflexes and do not evaluate the contribution of more higher-level cortical processes. We developed a simple rotational paradigm designed to evaluate vestibular function using psychophysical techniques. This technique incorporates an individual's perception of vestibular input, rather than isolating the responses of vestibular reflexes. We anticipate that this will allow another perspective into understanding patients with imbalance and offer important diagnostic and therapeutic opportunities.

Mean detection and discrimination thresholds for 0.3 Hz were greater than mean thresholds at 0.5 Hz for all velocities tested. This is consistent with the data from Grabherr, et al. (2008), which showed mean detection thresholds at frequencies lower than 0.5 Hz greater than mean detection thresholds above 0.5 Hz. Although our stimulus paradigm varied slightly from that described by Grabherr, et al. (2008), detection threshold values at 0.3 Hz and 0.5 Hz approximately match the values modeled by the fit of data from Grabherr, et al. (2008), and display the same frequency dependence of higher thresholds at lower frequencies. Grabherr, et al. (2008) explained this by suggesting that the information transferred by afferents is the limiting step in psychophysical performance. Because vestibular-nerve afferents have relatively low gains (and therefore presumably signal to noise ratios) at lower frequencies, the information they provide at low frequencies may be less reliable than the information provided at higher frequencies.

The variability of discrimination thresholds among participants was unexpected, particularly in that some individuals had thresholds at 0.5 Hz that were higher than thresholds for other individuals at 0.3 Hz at a given velocity. Within each participant, however, (with the exception of participant #1 at a single velocity) the discrimination thresholds were consistently greater at 0.3 Hz than at 0.5 Hz at each velocity. This suggests that some subjects are simply globally better at vestibular psychophysical tests than others. The implications of this for athletes and others in occupations requiring balance functioning is not yet known.

Discrimination thresholds measured across a multitude of tasks and sensory systems typically follow “Weber’s Law” in which the discrimination threshold increases as the standard value of comparison grows larger. The ratio between the threshold and the standard form the “Weber fraction,” which is then constant regardless of stimulus level (Gelfand, 2004).

Weber’s Law has been studied intensively in hearing. Identifying characteristics of the relationship between auditory stimuli and an individual’s perception of these sounds has furthered our understanding of the underlying mechanisms that contribute to auditory perception. Intensity and frequency DLs for normal hearing individuals have essentially been shown to follow Weber’s Law, with deviations generally at higher frequencies and intensities depending on the stimulus presented (Florentine, et al., 1987; Florentine, et al., 1993; Gelfand, 2004). Florentine, et al. (1993) found that intensity DLs for those with sensorineural hearing loss deviate less than those with normal hearing. Freyman and Nelson (1991) found no differences in deviation of frequency discrimination from Weber’s Law between those with sensorineural hearing loss and those with normal hearing. Weber’s Law has also been shown to exist in other modalities, as illustrated in a study evaluating the DL for perception of light (Gelfand, 2004).

The linear regression to the threshold at each velocity has a slope of approximately 0.01 at both 0.3 Hz and 0.5 Hz. This value represents the Weber fraction for perception of angular motion by the vestibular system. The dependence of discrimination thresholds on absolute velocity for vestibular perception is somewhat surprising, as the gain of vestibular afferents is preserved at a constant level across a broad range of angular velocities (Fernandez and Goldberg, 1971). This constant afferent signal has been believed to contribute to the VOR's ability to maintain an accuracy of better than 3 degrees per second even at high velocities in order to sustain stability of a visual image on the retina and prevent oscillopsia. It also is somewhat different than earlier findings, which indicated that discrimination thresholds at 0.5 Hz were maintained across a range of velocities (Mallery, Olomu, Uchanski, and Hullar, ARO abstract 2009). VOR gain has been shown to remain relatively constant across angular accelerations approximately up to 2000 degrees per second^2, where then it begins to decrease gradually (Weber, et al., 2008).

Several possibilities may explain this apparent discrepancy. The neural circuits dictating psychophysical responses and reflex eye stabilization may be distinct enough that their performance is not comparable. The steadily increasing error in the system at higher amplitudes may be still so small even at high amplitudes that vestibular performance is not compromised. The error, which increases along the range of velocities measured here, may asymptote at higher velocities. It is possible that these responses to angular acceleration may differ from responses to angular velocity. Other factors may also have contributed to these results, including potential physiologic differences at 0.3 Hz from 0.5 Hz, differences in the individuals tested in each study, and differences in the examiners performing testing. Finally, it must be noted that the 95% confidence intervals for the slope (Weber fraction) include zero for the 0.5 Hz data and nearly include zero for the 0.3 Hz. Further study is required before the applicability of Weber's Law to the perception of angular rotation can be verified.

Further assessment of the test-retest reliability of our paradigm and inter-rater reliability is required. Studies with larger sample sizes for a given population are warranted to establish normative data. There is also a need to establish a relationship between psychophysical measures and conventional vestibular testing. In addition, our paradigm is time-consuming and further investigation is needed to develop a more efficient protocol in order to consider its potential for clinical use.

Conclusion

Approximately one in every seven cases has no known etiology that can be determined using standard clinical measures currently in use (Kroenke, et al., 2000). This study evaluated discrimination thresholds of angular velocity in normal healthy participants. Results revealed higher discrimination thresholds at 0.3 Hz compared to discrimination thresholds at 0.5 Hz, and an increase in discrimination threshold with increasing angular velocity. These findings are anticipated to assist in developing more sensitive tests to diagnose patients with vestibular symptoms, and design therapeutic strategies for patients recovering from vestibular insults and with congenitally diminished vestibular function.

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