THE EFFECT OF ADULT AGING ON THE VESTIBULAR CONTROL OF STANDING BALANCE UNDER INCREASED COGNITIVE DEMAND

by

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A THESIS

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Brian Dalton

Postural control is an essential aspect of everyday life, but it can be compromised while multi-tasking or with altered attention, particularly among older adults. Age-related decrements within the sensorimotor system put older adults at greater risk of sustaining falls, however the effect of adult aging on the vestibular control of balance remains unclear. **Purpose:** The present study aimed to investigate the vestibular control of standing balance in old women under increased cognitive demand. **Methods:** Eight old (~70 years) and eight young (~23 years) recreationally active, healthy women stood on a force-plate with arms relaxed at their sides and head turned to the left for four 90-s trials while exposed to continuous electrical vestibular stimulation (EVS). Participants stood quietly with or without performing a cognitive task (mental arithmetic). The vestibular-evoked balance response was derived via anterior-posterior (AP) ground forces acting on the body and analyzed in the time (cumulant density) and frequency (coherence) domains. Total AP center of pressure (COP) displacement was measured as a means of quantifying balance stability. **Results:** Cumulant density peak medium latency amplitude was 42% larger in older women compared to the young for the single tasks ($p < 0.05$). Additionally, the medium latency peak amplitude increased by 13% from the single to dual task for the young ($p < 0.05$) but did not change for the old ($p = 0.700$). Coherence was elevated in older females compared to young at frequencies < 4 Hz during quiet standing. With the addition of a cognitive task, coherence was larger than the single task for the young women at frequencies < 2 Hz, but coherence did not change in the older females. Total AP COP displacement was not significantly different among age groups or tasks ($p > 0.05$).

Conclusion: The present findings in young adults likely resulted from the vestibular system acting as a compensatory mechanism to modulate balance control when cognitive resources are reallocated to a dual-task. Older females exhibit a greater vestibular-evoked balance response than young during single-task conditions, likely due to an increased sensitivity of the vestibular nuclei. While there was an increase in the vestibular-evoked balance response for the young during the single task as compared to the dual, the response in older females was not further elevated under the dual-task paradigm. Additionally, a lack of difference in total AP COP displacement among age groups or tasks suggests the possible involvement of additional compensatory mechanisms controlling for postural sway in old women under conditions of increased cognitive demand.

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Introduction and Background

Even for the simplest tasks of daily life, the body must utilize many different sensory systems in order to process the complexity of the external environment and orient the body to the space around it. By organizing and integrating these signals, the brain can make sense of our world. Maintaining standing balance is a basic, yet essential motor skill that often goes unnoticed in everyday life. The simple act of standing requires coordination of a variety signals from several sensory organs that must be incorporated seamlessly in the central nervous system to maintain smooth, controlled muscle function. Postural control during quiet standing is integrated by the central nervous system (CNS) using sensory information arising from visual (Judge et al., 1995; Fitzpatrick et al., 1994), proprioceptive (Judge et al., 1995), cutaneous (Kavounoudias et al., 2001), and vestibular (Pothula et al, 2004) inputs, as well as involvement from cognitive (Szturm et al., 2013), and central (Colledge, et al., 1994) feedback.

The vestibular system plays a crucial role in this process, as it is responsible for detecting linear and angular accelerations of the head. It has been shown that vestibular-evoked responses can be stimulated by externally applying electrical vestibular stimulation (EVS), while measuring the subsequent whole-body responses (Fitzpatrick & Day, 2004; Dakin et al., 2007; Mian & Day, 2009). Administration of this low-amplitude electrical current stimulates the vestibular nerve directly, bypasses the vestibular organs, and thereby produces a whole-body response due to the sensation of an imbalance (Fitzpatrick & Day, 2004). This error signal causes a convergence of sensory signals on the vestibular nuclei, resulting in a counteractive balance reflex observed by an increase in sway while standing (Fitzpatrick & Day, 2004). EVS is a safe and effective means of probing the human vestibular system, as it elicits a clear vestibular response without the need for invasive procedures nor with the appearance of lasting effects after removal of the stimulus (Fitzpatrick et al, 2004). The EVS response generates a characteristic biphasic pattern with two distinctive peaks, termed short and medium latency responses (Nashner et al., 1974; Dakin et al., 2007). These two outcome measures occur at slightly different times, with lower limb short latency postural responses arising approximately 60 milliseconds after the vestibular stimulus is applied, while medium latency occurs at about 110 milliseconds after EVS (Britton et al., 1993; Fitzpatrick et al., 1994; Welgampola & Colebatch, 2002; Luu et al., 2012; Dalton et al., 2014). It has been hypothesized these time delays are indicative of differences in descending pathways within the CNS. Britton et al. (1993) suggested the short latency peak is the motor response derived from the vestibulospinal pathway, while the prolonged effect from the medium latency is a manifestation of a vestibular-evoked balance response propagated along the reticulospinal tract. Additionally, other research has suggested a connection between frequency and the biphasic nature of the cumulant density function, with high and low frequency bandwidths corresponding to short and medium latency responses, respectively (Dakin et al., 2007). While the exact mechanisms behind these myogenic responses are yet to be determined, measurements of whole-body anterior-posterior ground forces can serve as a means of estimating the net result from all muscles involved in the vestibular postural response (Mian & Day, 2009).

Balance control is typically not an isolated task; rather, it is performed alongside secondary demands that require an individual to multitask. With divided attention, cortical activity in the brain is diverted to assess external cues, concurrent tasks, and body orientation in addition to the balance task (Szturm et al., 2013). This is a complex process that requires cognitive flexibility and fine motor control (Szturm et al., 2013). Recent research has suggested a link between motor deficits and increased cortical inhibition in the presence of a cognitive task (Holste et al., 2015), which could also indicate similar deficits during standing balance. A secondary cognitive task performed in conjunction with another experimental parameter, termed a dual task, diverts attention from the original task, which may cause structural interference due to the sharing or exchange of neural resources (Boisgontier et al., 2013). If the complexity of a dual task reaches the processing limits of the CNS, cognitive resources must be reallocated to accommodate the attention-demanding task, often resulting in declines in performance of one or both tasks (Boisgontier et al., 2013). A result of healthy adult aging involves the deterioration of central processing capacities, a severe limitation in a person's ability to successfully navigate their environment and maintain postural stability, particularly under conditions with complex motor and cognitive tasks (Boisgontier et al., 2013; Buchman et al., 2011). When this occurs, the body must either compensate with other functional systems or it will fail, a consequence often resulting injury (Lord & Sturnieks, 2005).

Both physical and cognitive degenerations lead to balance deficiencies in the elderly, a particularly concerning problem due to the debilitating consequences of age-related falls. In 2013, unintentional falls accounted for nearly 50,000 deaths in adults aged 65 years or older in the United States (Kramarow, 2015). According to the Center for Disease Control (2015), a staggering 2.5 million older adults are treated in emergency rooms every year due to fall injuries. Among those, 700,000 are hospitalized, ultimately costing $34 billion annually in direct medical costs. Hospitalization due to fall-related head trauma or bone fractures are substantial contributors to these costs as well, with 250,000 people hospitalized for hip fractures and over 95% of these fractures are a direct result of a fall (CDC, 2015). To help reduce these injuries and mounting healthcare costs, efforts directed towards fall-prevention programs based on physiological consequences of aging, could prove effective.

Age-related reductions in vestibular function may be critical for helping to diagnose and treat imbalance issues and falls. The involvement of somatosensory and visual systems in balance control among the elderly is well documented (Abrahamová et al., 2009; Judge et al., 1995; Ray et al., 2008; Shaffer and Harrison 2007), however little is known about the vestibular aging processes or associated consequences with age-related deterioration. Among the limited body of research concerning the effect of aging and the vestibular system, most conclusions are also based upon male populations. Women tend to be overlooked within the literature. Therefore, this study aimed to augment female-driven research and lessen the sex-based divide via recruitment of female subjects for both the young and old age-groups analyzed in this experiment. Knowledge regarding vestibular contributions to sensory impairment in older adults of both sexes could help in the establishment of intervention techniques and treatment plans to better gauge a patient's sensorimotor function and reduce the risk of subsequent falls. Therefore this study aims to investigate the contribution of vestibulo-motor pathways in maintaining quiet standing balance under an increased cognitive demand within an elderly female population.

Physiological Mechanisms of Standing Balance

In order to investigate the role of the vestibular system in standing balance, it is necessary to first understand the anatomical and physiological mechanisms involved in postural control. The vestibular organs are located in the inner ear within a system of passages and cavities in the bones of the skull (Fig. 1). Two unique and easily recognizable structures in the inner ear are the coiled-shaped cochlea and the three-part circular tubes of the semicircular canals. While the cochlea is involved in auditory sensation, its neighbors, the vestibular organs, detect rotational movement and linear acceleration of the head, often referred to as the body’s sense of balance (Tresilian, 2012; Fitzpatrick & Day, 2004).

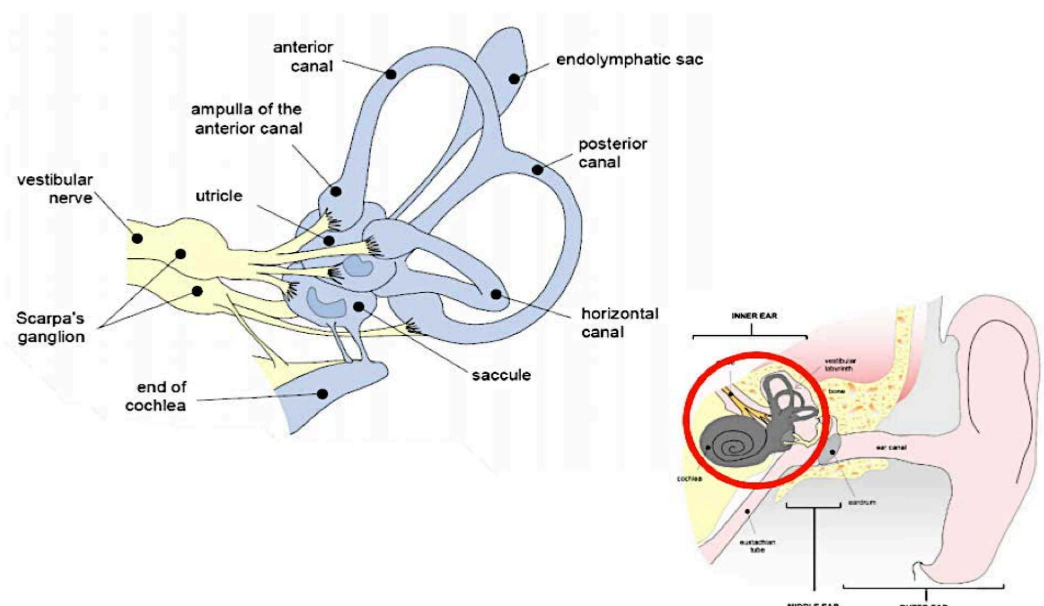


Fig. 1. Organs of the vestibular system

The mechanisms behind the vestibular system's role in postural control is of particular interest due to its involvement in common balance impairments, such as dizziness, vertigo, and general instability (Ishiyama, 2009). It is important to understand how the vestibular system functions, both anatomically and physiologically, in order to understand its role in mediating standing balance. As a whole, the vestibular system detects the position and movement of the head in space. It is responsible for angular and linear acceleration of the head, head and eye stabilization, and postural control (Fitzpatrick & Day, 2004). Rotational movement of the head is detected by three semicircular canals located in perpendicular planes. The semicircular canals, filled with endolymph fluid, detect rotational movement of the head from the deflection of tiny hair cells composed of stereocilia and one large kinocilium (Fig. 2). The left and right vestibular organs coordinate excitatory or inhibitory signals along the nerve to determine the direction of movement.

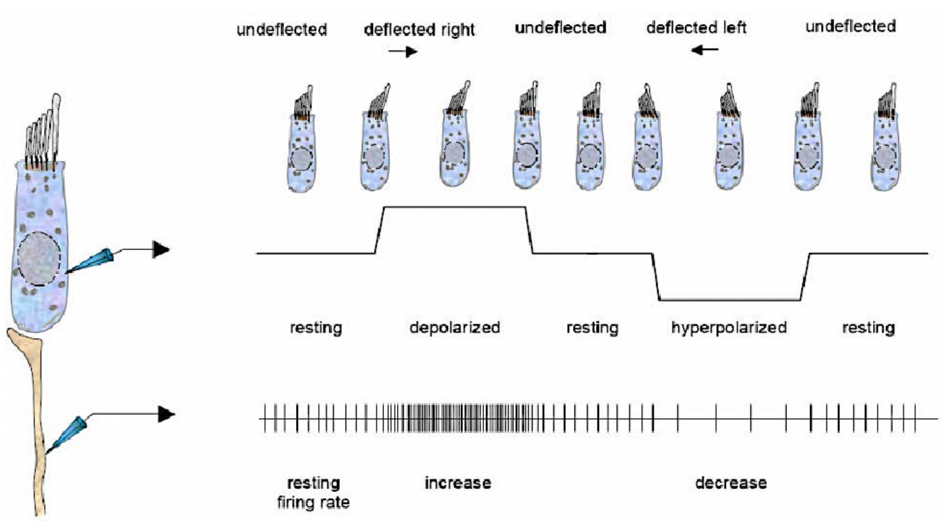


Fig. 2. Effect of deflecting semicircular canal hair cells on nerve firing rates

For example, imagine a person looking over their left shoulder by rotating the head to the left. In the left horizontal semicircular canal, counterclockwise rotation of the head causes a clockwise displacement of the endolymph fluid and subsequent deflection of the stereocilia toward the kinocilium. This produces a depolarizing effect and a resultant excitation of the left vestibular nerve. The opposite process is produced in the right semicircular canal, thus causing hyperpolarization and an inhibitory response of the right nerve. These signals are transmitted to various areas of the central nervous system (CNS) and ultimately cause the perception of head rotation, even without visual cues.

Linear acceleration on the other hand, is detected through otolith organs, called the saccule and utricle, which are small egg-shaped structures at the base of the semicircular canals lined with specialized sensory hair cells that project into a gelatinous fluid. Resting on top of the membrane are small calcium carbonate crystals. Together, the saccule and utricle are sensitive to gravity and detect vertical and horizontal linear accelerations, respectively. Two common every-day activities that utilize these otolith organs include acceleration or deceleration while driving a car (utricles) and riding in an elevator (saccules). The body can sense these movements, without the aid of visual cues, due to the contribution of the utricles and saccules. Head tilt and translational acceleration are detected when the membrane deforms and the embedded hair cells are deflected in one direction or the other, which produces an associated change in neuronal firing rate (Fig. 3).

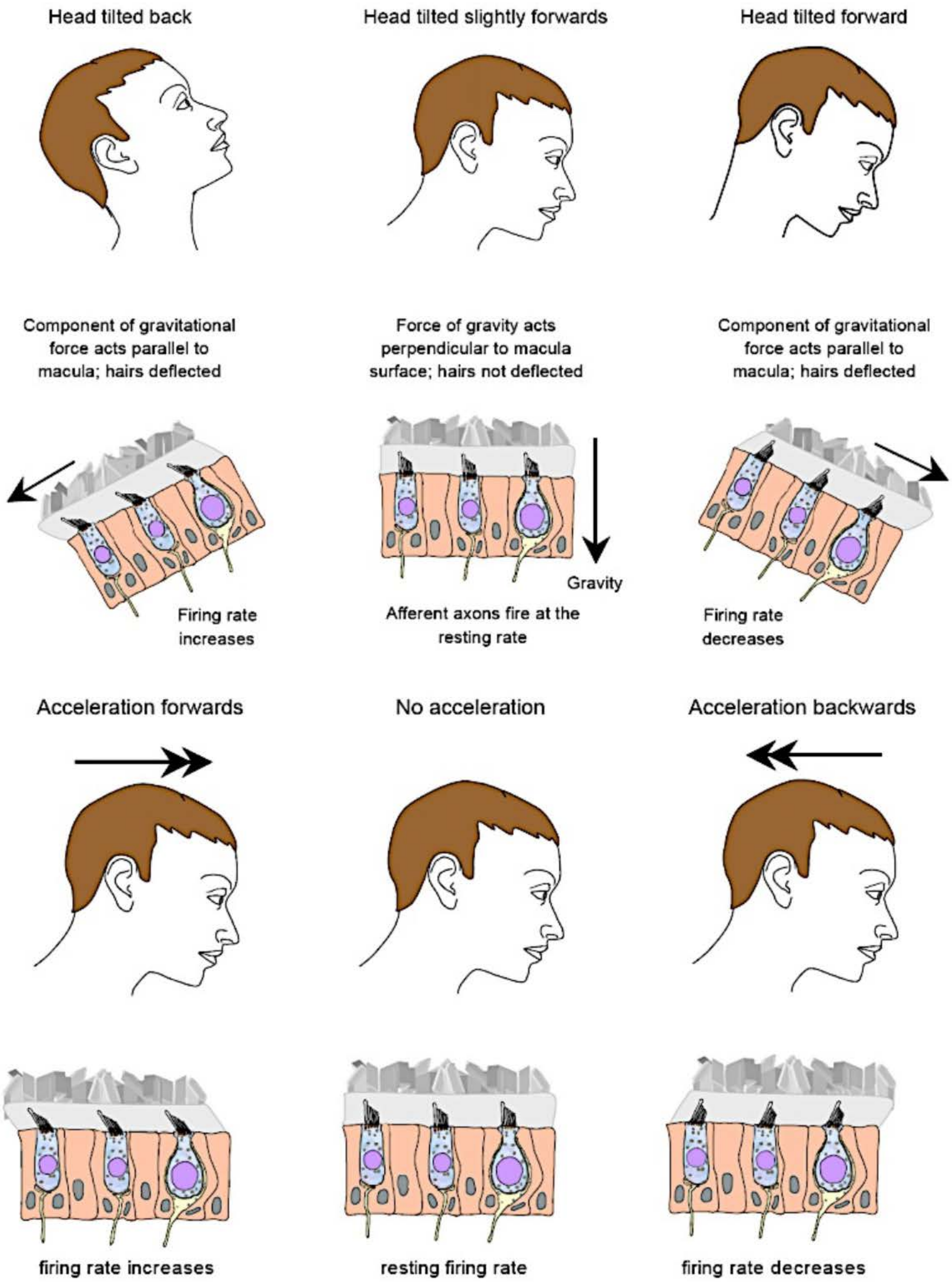


Fig. 3. Effects of angular and linear acceleration on the membrane of the utricle

Balance control involves not only integrations of information from external feedback, but it is also influenced by cognitive demand. Factors including navigation of the external environment, individual motivation, and variations in attention control heavily influence the preparation and execution of body movement (Buchman et al., 2011; Hyndman et al., 2003; Jacobs et al., 2007; Park et al., 2015). Typically, one does not solely concentrate on maintaining balance. Instead, balance is monitored while performing congruent tasks such as walking, talking, reaching for objects, searching for things, navigating obstacles, or any other task required in everyday living that diverts attention away from balance control. Information coming from the vestibular system is integrated among these concurrent inputs within neural pathways projecting from the hair cells to vestibular nuclei of the brainstem (Fitzpatrick & Day, 2004). The vestibular nuclei are clusters of cell bodies located along the brainstem. Sensory signals are projected onto these nuclei before they are integrated within various target regions of the central nervous system (Fig. 4). The precise neural pathways utilized for balance control remain somewhat unclear and contemporary research lacks complete understanding regarding the specific cognitive structures involved in attention-dividing tasks (Al-Yahya et al., 2011).

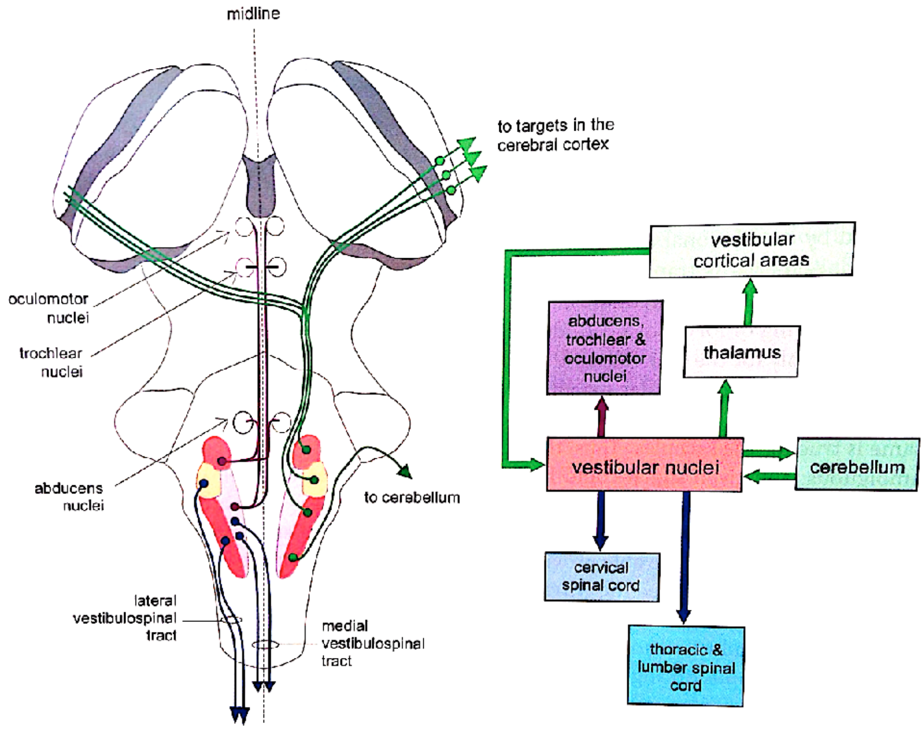


Fig. 4. Connectivity of the vestibular nuclei

Some theories (Murnaghan et al., 2014) suggest that balance control is modulated by lower levels of the brain (brainstem and spinal cord) while others claim there is an influence by the cerebral cortex (Varghese et al., 2015). In postural control, high-level brain activity corresponds to voluntary postural adjustment, while lower-level integration involves automatic, involuntary 'micro-adjustments' that occur below conscious control (Boisgontier et al., 2013). Some researchers have hypothesized postural sway is modulated by a passive response from the muscles acting in a spring-like manner, almost entirely reducing the need for central control. (Winter et al., 1998). However, it seems precise coordination from predictable muscle activity as well as internal and external sensory feedback for the brain to continually monitor the body's upright posture (Murnaghan et al., 2014; Jacobs et al., 2007). In all, balance control is a multi-dimensional state that seems to involve both cortical and sub-cortical areas of the brain. Despite the apparent simplicity of quiet standing, the body is continually integrating sensory and cognitive information about the body and its environment to maintain postural equilibrium. Failure of this process is cause for the most interest and relevance to future experimental investigation in order to learn how to prevent and treat potential impairments due vestibular dysfunction.

Physiological Deteriorations Associated with Aging

For many adults, the aging process brings with it general physical decline accompanied by reduced abilities to maintain strength and stability of the body (Sturnieks et al., 2008). Overall weakness, dulled sensory perception, delayed reaction time, increased postural sway, and changes in gait patterns are common difficulties facing the older adults (Sturnieks et al., 2008). Both structural and functional deteriorations of the somatosensory system are natural consequences of healthy adult aging and are potential contributors to postural instability in older adults. Based upon clinical and laboratory studies, it has been noted that the sensory system declines in a non-uniform and quite diverse manner due to natural aging (Shaffer and Harrison 2007). Some structures are more affected by age than others. Auditory and vestibular hair cells are particular vulnerable to age-related deterioration due to the high amount of mitochondrial density, increasing the risk of producing damaging toxic chemicals as a result of aging (Ishiyama, 2009). Hair cells are also more susceptible of undergoing vascular ischemia (lack of blood flow) due to limited circulation within the inner ear (Ishiyama, 2009). Moreover, the highly specialized nature of the sensory hair cells and their corresponding neuronal connections make them highly unlikely to regenerate after damage (Ishiyama, 2009).

Age-related deteriorations also include a preferential deterioration of large, myelinated neurons and their associated receptors (Ishiyama, 2009; Rosenhall, 1973). Myelination is a process by which neuronal axons are covered in a myelin sheath, a fatty tissue insulator that allows electrical impulses to travel quickly along the nerve. With demyelination, nerve conduction velocity decreases or may stop all together, resulting in serious neurological disorders. Evidence has suggested that sensory neurons, particularly primary myelinated fibers, deteriorate prior to motor neurons in healthy adult aging (Schaffer et al., 2007). These findings also correlate with many other clinical findings in which older adults exhibit impairments in proprioception as well as vibration and discriminative touch, all sensations that rely upon electrical signal propagation along large, myelinated axons (Schaffer et al., 2007). Progressive age-related declines in both hair cell density and demyelination reduce the peripheral input to the vestibular nuclei, therefore, it has been postulated that the vestibular system becomes progressively sensitive to stimuli in older adults as a functional adaptation to compensate for reduced sensory input (Jahn et al., 2003; Welgampola and Colebatch, 2002).

Research is divided when it comes to differences in central processing within young and old populations, with most clinical studies yielding significant impairments in postural control in healthy older subjects in comparison to their younger counterparts, while other studies have found no such differences (Boisgontier, et al., 2013). Boisgontier et al. (2013) reviewed fourteen studies aimed at demonstrating age-related differences in the central processing of postural control under dual-task paradigms. They found that older adults are able to successfully control posture under stable conditions nearly as well as younger subjects, however there is a trend (although not always statistically significant) of postural performance declines in older adults during dual task conditions in comparison to young adults. From a cognitive standpoint, it has been hypothesized that older adults require greater levels of controlled (voluntary) processing and therefore utilize more cognitive resources for balance tasks than young (Boisgontier, et al., 2013). Therefore, if a secondary task is involved while standing, cortical resources are divided, leaving fewer resources designated for balance control (Boisgontier, et al., 2013; Ruffieux et al., 2015). This phenomenon could result in an increased risk of sustaining a fall within an older population, particularly while subjects are multitasking.

Without proper motor signals and efficient cognitive control, movement precision is greatly impaired. Older adults, both those with and without a history of falls, demonstrate increased postural sway and larger center of pressure (COP) displacement during quiet standing than healthy younger subjects (Laughton et al., 2003). With so many factors involved in balance control, it is difficult to pinpoint the precise cause of falls. However, it has been suggested that the vestibular system is, at least in part, responsible (Ishiyama, 2009). In a study performed by Pothula et al. (2004), it was found that out of the patients who had sustained unexplained falls, 80% showed signs of vestibular impairment. Additionally, Murray et al., (2005) found that fallers admitted to the Emergency Department demonstrated symptoms of underlying vestibular dysfunction and were at significantly higher risks of sustaining future falls. These vestibular impairments, coupled with reduced muscle volume and progressive weakness due to advanced age (Baudry et al., 2012; Porter, 1995), are indicative of the high risk of falls observed in the elderly (Pothula et al., 2004). Further investigation is needed in order to fully understand the role of the vestibular system in healthy adult aging.

Purpose and Hypothesis

The human vestibular system provides information about the orientation of the head and neck in space and pertains to the ability to maintain upright posture. Vestibular impairments may have a significant effect on age-related instability resulting in injury due to falls. The purpose of this study was to investigate the contribution of vestibulo-motor pathways in maintaining quiet standing balance under increased cognitive demand in older adults. It was hypothesized the older adults would exhibit 1) a greater vestibular-evoked balance response in anterior-posterior ground forces during quiet standing, and 2) a larger increase in the vestibular-evoked balance response with the addition of a secondary cognitive task than their younger counterparts.

Methods

Participants

Eight young and eight old recreationally active, healthy women volunteered for this study (Table 1). The older participants lived independently in the community and were free from neuromuscular and orthopedic injuries/disorders. Written and oral consent were obtained from all subjects prior to participation, in accordance with the Declaration of Helsinki and all procedures were granted approval by the local institutional review board.

Table 1: Participant demographics

	Young	**Old**
Age (years)	22.6 ± 1.8	69.7 ± 6.7
Height (cm)	164.8 ± 6.9	159.2 ± 5.2
Mass (km)	60.8 ± 7.1	63.3 ± 8.3
Body Mass Index (BMI)	22.4 ± 2.6	25.0 ± 3.4
Total Body Fat (%)	29.3 ± 6.7	37.6 ± 6.3
Lean Tissue Mass (kg)	40.84	37.19

Experimental Overview and Procedures

Participants who qualified and consented completed two testing sessions, 1) baseline tests to determine body composition and muscle function, and 2) the experimental session to analyze vestibular balance control.

Body composition and muscle function. For the initial testing session, participants underwent a whole-body composition scan using a dual-energy X-ray absorptiometry (DEXA) performed by a trained and licensed technician to quantify bone mineral density, fat free mass, and fat mass. During the same visit, isometric and dynamic knee extensor muscle function was tested using a Biodex System 3 multi-joint dynamometer (Biodex Medical Systems, Shirley, NY). To limit extraneous body movements, the participants were securely fastened to the chair with inelastic straps around the right thigh, hips and shoulders. The knee joint was aligned with the dynamometer's axis of rotation and an inelastic strap was fastened around the shank, ~2 cm superior to the malleoli, to secure the leg to the knee attachment of the dynamometer.

Once set-up was complete, participants performed three 5-s maximum voluntary isometric contractions (MVC) of the right knee extensors from a seated position with the hip and knee angle set at 90º. An additional MVC effort was performed if the second and third attempts varied in peak torque amplitude by more than 5%. During all maximal efforts, participants were provided visual feedback of the torque via a computer monitor and verbally encouraged by the investigator. A 3-min rest period followed each MVC attempt.

Next, participants rested for at least 5 minutes and then they performed isotonic shortening contractions of the knee extensors. To ensure reliability of the dynamic task (Power et al. 2011), participants were familiarized with four to six practice dynamic knee extensions at a resistance of ~20-30% MVC. Following a three-minute rest and to determine the torque-velocity relationship, participants performed pairs of maximal-effort isotonic knee extensions at a relative resistance of 10, 20, 30, 40, 50% MVC derived from the MVC torque through a 70° range of motion of the knee (80° start position to 150° end position; 180° being terminal knee extension). At the end range of motion for each isotonic shortening contraction, the participant relaxed the knee extensors fully and the leg was returned passively to the start position. Participants rested 30 s between each pair of dynamic contractions. The order of contractions was randomized for each participant. Participants were instructed to contract the knee extensors as fast and as hard as possible, encouraged verbally, and provided visual feedback of the angular velocity for all dynamic efforts. All knee extensor torques, angular velocities and positions were sampled at 1010 Hz using a 16-bit analog-to-digital converter (Micro 1401-3; Cambridge Electronic Design, Cambridge, UK) and stored online using Spike2 version 8 software (Cambridge Electronic Design, Cambridge, UK).

Vestibular control of balance. During the second testing session, participants were exposed to continuous electrical vestibular stimulation (EVS) while deprived of vision and external support. After placement of the EVS electrodes, participants underwent a 30-s familiarization trial of EVS while seated. Subjects subsequently completed seven 90-s trials, under various conditions. For the first and last trials, participants sat quietly and completed a cognitive task consisting of a set of double-digit addition and subtraction questions. For the second trial, participants stood quietly, while completing the cognitive task. These three trials served as a control for cognitive task accuracy. Next, participants completed 4 additional trials in random order. Two trials included the participant receiving EVS while performing the cognitive task; whereas for the other two trials, participants were exposed to EVS without performing the secondary cognitive task. Rest periods were given between trials to prevent the effects of fatigue.

For all trials, participants stood upright with feet together (medial malleoli touching) on a force plate (OR6-5-2000, Advanced Mechanical Technology Inc., Watertown, MA, USA). Participants were instructed to stand in a relaxed position with their arms resting by their sides and head rotated 90° to the left (towards the cathode) and tilted ~19° above horizontal to align the postural response in the anterior-posterior direction (Cathers et al., 2005; Mian at al., 2009). This orientation (Fig. 5) maximizes the vestibular-evoked balance response along the plane of motion of the ankle plantar flexors and dorsiflexors, the primary muscles involved in modulating postural sway. Head position was maintained via a laser affixed above the right ear and verbal cues from the investigators. For all trials, anterior-posterior (AP) ground reaction forces acting on the body were measured to determine the vestibular-evoked balance response (Dalton et al. 2014; Mian & Day 2009).

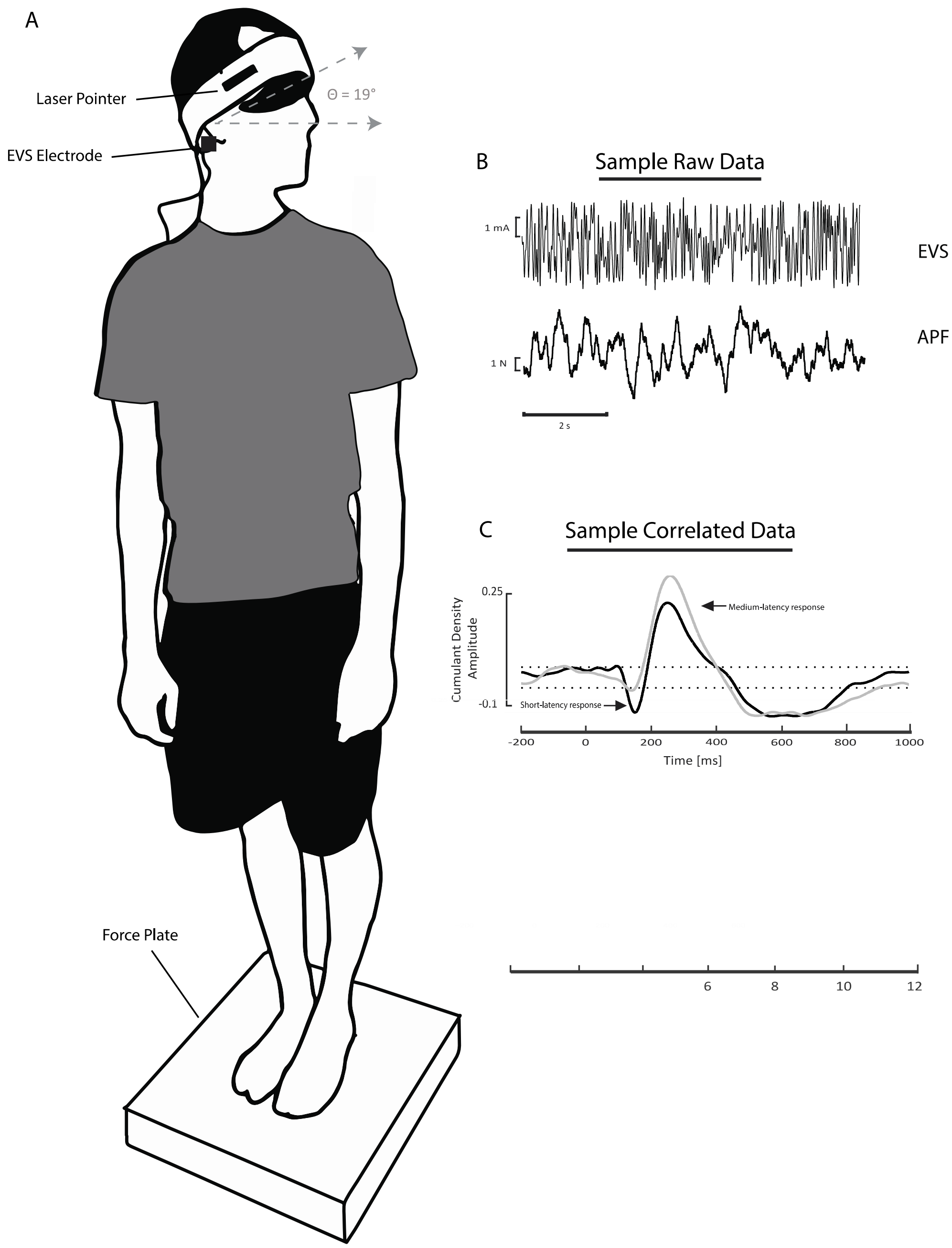


Fig. 5. Experimental set-up

A) Experimental set-up showing the head rotated 90° to the left and tilted upward 19° from horizontal. A laser pointer was secured to the head above the right ear and oriented to Reid's plane. Thus, the vestibular-evoked response was primarily aligned in the anterior-posterior direction. B) Sample 10s traces of electrical vestibular stimulation (EVS) and unprocessed anterior-posterior forces (APF). C) Individual vestibular evoked balance responses via cumulant density and coherence functions in young (black) and old (grey) adults during a single task.

Vestibular Stimulation

Carbon-rubber electrode pads (contact area: 12 cm^2), coated with electrode conducting gel (Spectra 360; Parker Laboratories, Fairfield, NJ, USA) were positioned bilaterally over the mastoid processes to deliver a continuous, binaural electrical current, varying randomly in both frequency (range: 0-20 Hz) and amplitude (peak to peak: ±2.50 mA; root mean square: 1.13 mA). The electrodes were secured using Durapore tape (3M, St. Paul, MN, USA) and an elastic bandage. The EVS signal was created using LabView software (National Instruments, Austin, TX, USA) and delivered via an isolated constant current stimulator (±10 V input, ±10 mA output, DS5, Digitimer Ltd, Welwyn Garden City, UK). Previous studies (Dakin et al., 2007; Dalton et al., 2014; Forbes et al., 2013; Luu et al., 2012) using similar EVS signals consisting of similar frequencies and amplitudes utilized in the present study have demonstrated significant vestibular-evoked whole-body postural responses. Once a stochastic EVS signal was created, the same waveform was used to generate vestibular-evoked balance responses for each participant for every trial to ensure that inter-trial and inter-subject frequency bands were identical.

Anterior-Posterior Ground Body Forces and Pressure of Displacement

Anterior-posterior forces acting on the body were measured using a triaxial force plate and sampled online at 2048 Hz. Force data were mean-deviated and low-pass filtered digitally (30 Hz; MATLAB, Mathworks, Natick, MA, USA) offline.

Cognitive Task

The cognitive task consisted of double-digit integer addition and subtraction questions produced by a random number generator (LabVIEW, National Instruments, Austin, TX, USA). Questions were delivered verbally, at 10-s intervals, by the investigators commencing at the onset of EVS for a total of 9 questions per trial. For each question, participants had 10 s to respond. Participants were not given any indication of the accuracy of their responses during the entirety of the experiment. If participants failed to answer within the allotted time, the question was recorded as incorrect, and a subsequent equation was provided.

Data Analysis

Isometric MVC strength was assessed using peak torque amplitude. Power was calculated as the product of instantaneous torque (Nm) and angular velocity (rad/s). Peak power, at each relative resistance of the dynamic knee extensions, was measured from the contractions with the highest instantaneous value. Maximal power was considered as the highest peak power value across the range of resistances; whereas maximal velocity was taken from the 10% MVC shortening contraction.

The AP forces were used to characterize the vestibular-evoked balance responses. Exemplar data traces are provided in Fig. 5. The sampled AP forces (Fy) were time-locked to the EVS onset and trials of the same condition were concatenated to create data records of ~180 s (segment length: 2 s and resolution: 0.5 Hz) for each participant. The concatenated data were used to estimate relationships between the input (EVS signal) and the motor output in the frequency (coherence) and time (cumulant density) domains, which were derived using an archive of MATLAB (MathWorks, Natick, MA) functions based on multivariate Fourier analysis (NeuroSpec, http://www.neurospec.org). For visual display purposes and further data analysis, coherence and cumulant density functions were estimated using concatenated data across all participants for each age group.

To explore the frequency bandwidth of the vestibular-evoked balance response between age groups and cognitive tasks, coherence values were estimated. Coherence is a measure that represents the linear relationship between an input (i.e., EVS) and an output (i.e., AP forces) across a given frequency range. For every frequency data point, coherence varies from 0 (no linear relation) to 1 (linear system containing no noise). Coherence between the stimulation input and the AP forces acting on the body are significant when values exceed the 95% confidence limit, which were estimated from total segments per participant to determine frequencies that are significantly different than 0 (Halliday et al., 1995). Because coherence functions are essentially normalized for the magnitude of the output, stochastic EVS is a better method to compare different age groups in comparison with traditional galvanic vestibular stimulation.

To estimate time domain relationships, cumulant density functions were derived between the EVS and motor output (AP forces). A cumulant density estimate is a cross correlation-like measure and is interpreted as an associative rather than a causal relationship. Subsequently, the EVS–AP forces cumulant density estimates represent related responses that hold no physical values. Cumulant density estimates were calculated by transforming the cross-spectra between EVS input and AP forces acting on the body (output) into the time domain. Next, the amplitudes of the cumulant density functions were normalized by the product of the vector norms of the EVS signal and AP forces. This normalization method transforms the cumulant density values into an equivalent of a cross-correlation (r values confined between −1 and 1). Thus, this normalization procedure allows for a reasonable comparison between age groups that are not impacted by the known differences in lower limb muscle activation during standing balance (Baudry et al., 2012, 2014; Benjuya et al., 2004; Laughton et al., 2003). To determine significance of the cumulant density functions, 95% confidence intervals were derived for individual participants and evaluated on a participant-by-participant basis (i.e., when the peak amplitude values of the short and medium latencies exceeded the derived confidence intervals). The short latency peak amplitude represents the first peak (or trough) of the cumulant density function; whereas the peak amplitude of the medium latency response is the second peak (or trough) value of opposite polarity (Fig. 5).

To compare the main effect of age for the time domain, unpaired T-tests were conducted for the short and medium latency peak amplitudes of the cumulant density function EVS–AP force along with 95% confidence intervals for the difference in means. Differences observed in the coherence functions between dual- and single-task trials were assessed using the ‘Difference of Coherence’ subroutine in NeuroSpec 2.0 (Rosenberg et al., 1989; Amjad et al., 1997). This analysis compares the standardized differences between the dual- and single-task coherence values and the 95% confidence limits. Statistical significance was derived from data that exceeded the 95% confidence intervals. Data above the upper limit trend towards the single task, while data exceeding the lower limit are associated with the dual. Statistical significance was set at $p \leq 0.05$. Descriptive statistics are reported as means ± standard deviations.

Results

Strength and Power

Maximal voluntary contractions (MVC) and maximal power and velocity values were all statistically higher in young compared to old females ($p < 0.05$; Table 2).

Table 2: Maximal power and velocity during isometric MVC.

	Young	Old
***MVC (Nm)**	152.2 ± 12.2	100.3 ± 34.9
***Maximal Power (Watts)**	385.8 ± 52.8	236.0 ± 52.4
***Maximal Velocity (°/s)**	399.7 ± 14.1	351.0 ± 43.8

(*) = denotes statistically significant differences between age groups.

Time Domain

The cumulant density function revealed significance (i.e. short and medium latency peak amplitudes exceeded 95% confidence intervals) in all participants for the anterior-posterior ground reaction forces outcome measure (data not shown). The older females exhibited 42 and 30% larger peak medium latency amplitudes than the young for both the single ($p = 0.003$) and dual tasks ($p = 0.034$), respectively (Fig. 6). Further, the medium latency peak amplitude increased by 12.7% from the single to dual task for the young ($p = 0.047$), but did not change for the old ($p = 0.700$; Fig. 7A, 7B). The short latency peak amplitudes were not statistically different between age groups or task ($p > 0.05$; Fig. 7A, 7B).

Frequency Domain

The coherence function reached significance (95% confidence limit) in all participants (data not shown). Significant coherence values spanned frequencies between 0 and 12 Hz for single and dual tasks in both age groups. While operational frequency bandwidths did not differ between age groups, the older adults exhibited larger coherence values than young for most frequencies < 4 Hz (Fig. 6). For the dual task, coherence was larger than the single task for the young females at frequencies < 2 Hz, but no differences were detected in the older females (Fig. 8).

Anterior-Posterior Center of Pressure

Mean total AP COP displacement was not significantly different between task conditions in either young or old participants or between age groups ($p > 0.05$; Table 3).

Table 3: Anterior-posterior center of pressure (COP)

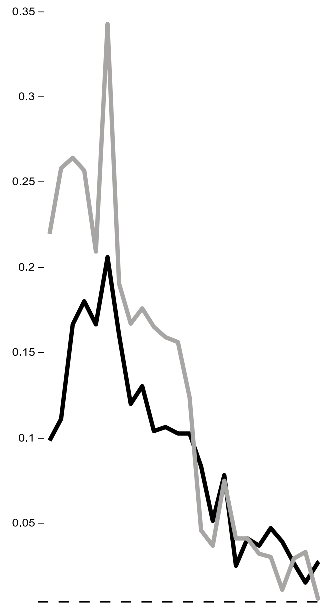
	Young	**Old**
Control (m)	2.83 ± 1.65	2.45 ± 1.31
Single Task (m)	2.84 ± 1.28	2.42 ± 1.02
Dual Task (m)	2.85 ± 1.33	2.39 ± 1.04

Cognitive Task

Participants answered an average of approximately 55% of the questions correctly across trials (Table 4). No significant differences were found between age groups or experimental conditions ($p > 0.05$).

Table 4: Cognitive task accuracy

	Young	Old
Seated (%)	55.6 ± 18.6	52.8 ± 29.5
No EVS (%)	60.4 ± 13.1	56.9 ± 20.1
EVS (%)	50.0 ± 18.5	52.1 ± 17.8
Seated (%)	55.6 ± 17.2	54.2 ± 21.8



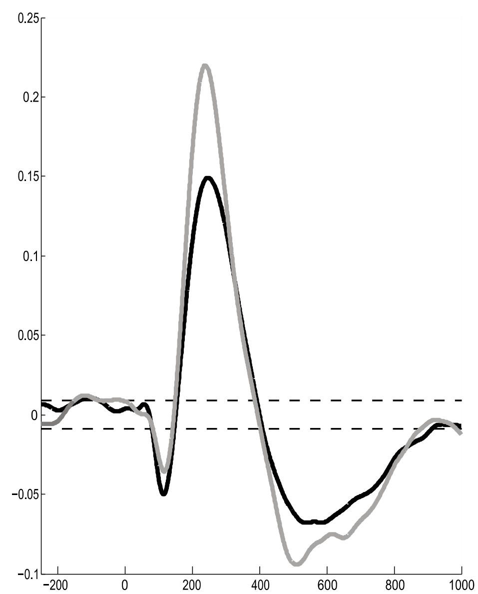


Fig. 6. Vestibular-evoked responses from concatenated data during a single task

A) Vestibular-evoked frequency responses from concatenated data among all participants in both the old (grey line) and young (black line) participants. B) Difference of coherence reached significance at frequencies < 4 Hz. C) Vestibular-evoked responses within the time domain in young (black) and old (grey) participants. D-E) Peak short latency (unfilled boxes) and peak medium latency (filled boxes) values in both young and old participants. A significant difference (*) was found between young and old adults in the medium latency response.

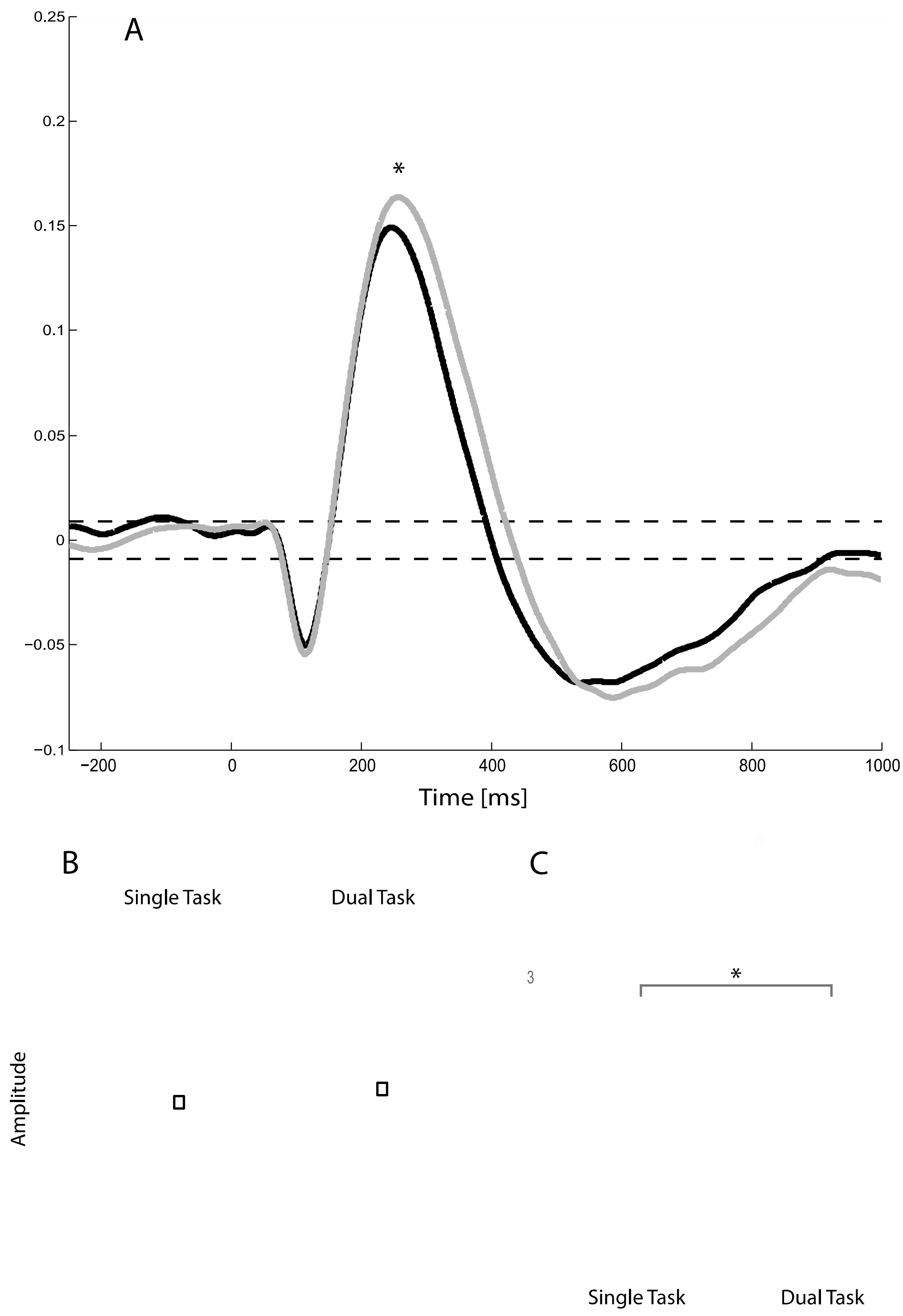


Fig. 7A. Vestibular-evoked time domain responses for single/dual tasks in young adults

A) Vestibular-evoked time domain responses for single- (black line) and dual-task (grey line) paradigms. B-C) Peak short latency (unfilled boxes) and peak medium latency (filled boxes) values. Significant differences between conditions are denoted by (*).

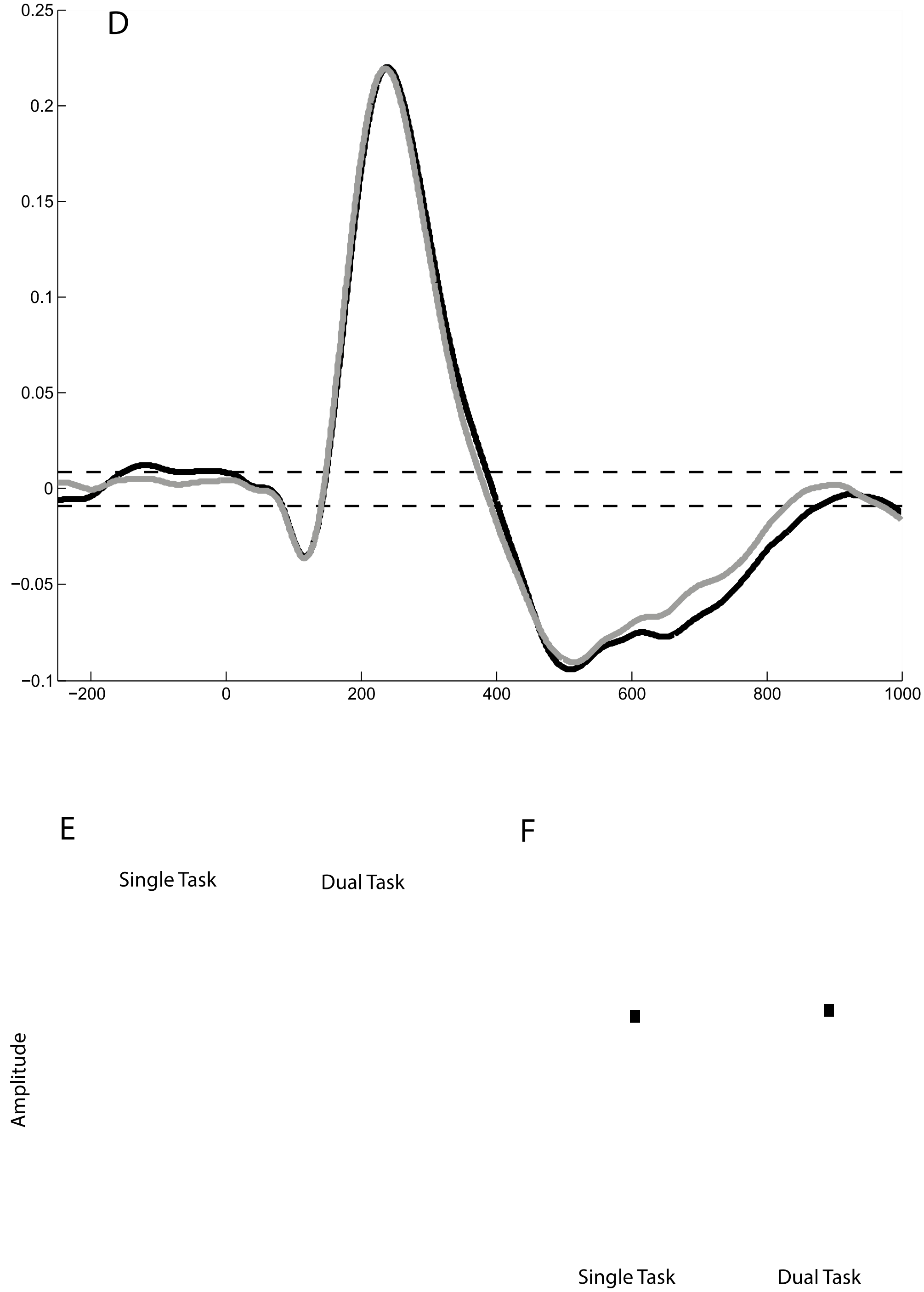


Fig. 7B. Vestibular-evoked time domain responses for single/dual tasks in old adults

D) Vestibular-evoked time domain responses for single- (black line) and dual-task (grey line) paradigms. E-F) Peak short latency (unfilled boxes) and peak medium latency (filled boxes) values. No significant differences were found between conditions.

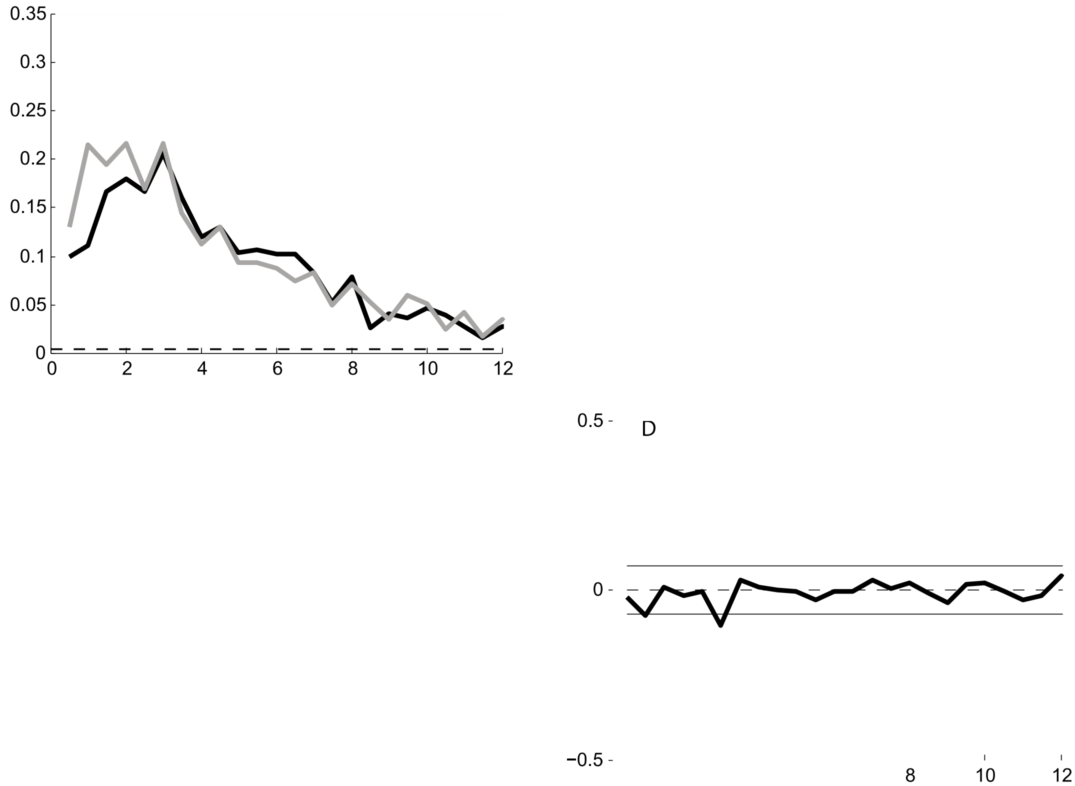


Fig. 8. Vestibular-evoked frequency responses between single and dual tasks

A) Vestibular evoked balance response in young adults during the single (black line) and dual (grey line) tasks. B) Difference of coherence in young participants showed significance between tasks at frequencies < 2 Hz. C) Vestibular evoked balance response in old adults during the single (black line) and dual (grey line) tasks. D) Difference of coherence for older adults showed no significance across the frequency bandwidth.

Discussion

The aim of the present study was to assess the effect of adult aging on the vestibular control of standing balance under increased cognitive demand. In order to accomplish this, the relationship between the EVS and AP forces (motor response) was derived within the frequency (coherence) and time (cumulant density) domains. The current findings supported my hypothesis that: 1) the older females would exhibit a larger vestibular-evoked balance response than young, as represented by the medium latency peak amplitude (Fig. 6). In contrast to the young females, the older females did not exhibit a larger vestibular-evoked balance response during the dual than single task. These findings indicate that there is an age-related increase in excitability of the vestibular nuclei during quiet standing. However, the vestibular-evoked balance response does not further increase during increased cognitive demand in older females, which may relate to the involvement of one or more additional physiological mechanisms in the regulation of postural sway during quiet standing.

The cumulant density function was utilized in order to investigate an associative relationship between the EVS and the resultant motor output within a time domain. Greater values in cumulant density represent a stronger association between the input signal and the motor output. Vestibular-evoked balance responses manifest in a biphasic pattern, termed short and medium latencies (Dakin et al., 2007). The medium latency component is thought to represent the postural reaction to the vestibular error signal propagated via the reticulospinal pathway (Britton et al., 1993; Marsden et al., 2002; Mian and Day, 2009). The timing and amplitude of these responses in the present study confirm and extend the results from older men (Dalton et al., 2014) by now adding results from older females.

In the present study, older females exhibited a larger vestibular-evoked whole-body balance response, as demonstrated by a larger peak medium latency amplitude than the young (Fig. 6). Several working theories have been proposed to explain the mechanisms behind this increased postural response. Healthy adult aging is associated with progressive loss of vestibular hair cells (Merchant et al., 2000) and cell body densities at the vestibular nuclei, neuronal degeneration in the vestibular nerves (Bergstrom, 1973) and large myelinated fibers (Rosenhall, 1973), as well as decreases in synaptic densities between vestibular-cerebellar connections (Bertoni-Freddari et al., 1986). Research has suggested that increases in the medium latency amplitude in older adults is likely due to a heightened sensitivity of the vestibular nuclei, which may act as an adaptive mechanism to combat age-related sensory losses (Jahn et al., 2003; Welgampola and Colebatch, 2002; Shaffer and Harrison, 2007). Similarly, increases in vestibular-evoked balance responses in older adults could also be due to alterations in perception of the stimuli (Menant et al., 2012) or variations in anxiety (Brown et al., 2006) and attentional demand (Woollacott and Shumway-Cook, 2002). As such, heightened cortical processing or alterations in muscle activation patterns during quiet standing could be tied to the variations observed in postural responses between old and young adults.

This enhanced sensitivity could thus maintain postural stability despite reduced peripheral input. The administration of EVS bypasses the vestibular organs so that all participants receive identical error signals and thus, the effect of varying function of hair cells is eliminated as a potential difference between age groups. Older adults with heightened central sensitivity or altered perception, would therefore be expected to present with a larger vestibular response to the same electrical signal than their younger counterparts, as demonstrated by the results of the present study. Healthy adult aging is also accompanied by increases in cortical processing (Baudry et al., 2012; Benjuya et al, 2004) and alterations in motor control strategies during quiet standing (Baudry et al., 2014; Benjuya et al., 2004; Laughton et al., 2003) as well as reductions in muscle mass (Aagaard et al., 2010). While subjects in the present study showed no differences in lean tissue mass between old and young females (Table 1), there were significant decreases in maximal power production in the old compared to young (Table 2). These consequences of adult aging likely result in the exaggerated compensatory vestibular balance response observed in the old compared with young.

The young participants had an elevated medium latency response during the dual task, however for the older females, there was no difference between the cognitive-task conditions (Fig. 7). However, it is also important to note that total AP COP displacement was not statistically different between age groups or trials. The findings within the young females, adds further support to the likelihood that the vestibular control of standing balance may act as a compensatory mechanism to offset postural imbalances often exhibited during dual-task conditions with increased cognitive demand (Bernard-Demanze et al., 2009; Lajoie et al., 1996; Marsh and Geel, 2000; Swan et al., 2004; Teasdale et al., 1993). It is possible that the vestibular system can modulate the postural response up to a certain point, but it may reach a ceiling due to the consequences of healthy adult aging, so there is no change in the medium latency response between tasks for the older females. However, as there were also no observable differences in the AP COP displacement between tasks in the old women, it is likely there is the presence of an additional compensatory mechanism modulating postural control. Further research would benefit from pursuing this hypothesis.

Coherence was utilized to assess the relationship between the vestibular stimulation and the associated motor output over various frequencies. This function not only reveals the associative characteristics of the vestibular-evoked balance response and the vestibular error signal across an operational frequency bandwidth, but it also depicts the strength of that association. Difference of coherence is a statistical analysis that was used to characterize significance between coherence values. Statistically significant differences were found between the young and older females at most frequencies, < 4 Hz, but not at higher frequencies for the single task. Similar to cumulant density, high coherence values in the older adults may indicate an increase in sensitivity to the vestibular nuclei than compared to young adults. These results correlate with the significant difference found at the medium, and lack of a difference at the short latency peak, since it has been hypothesized that short and medium latencies are associated with high and low frequencies, respectively (Dakin et al., 2007). The coherence function revealed similar operational bandwidths between young and old subjects, as the function exceeded the 95% confidence interval between 0 and 12 Hz for both groups. Greater coherence values were found in dual-task conditions at frequencies < 2 Hz in the young, but not in the old adults, which corresponds to the cumulant density results. This lack of a change between single and dual tasks in older adults suggests that perhaps the vestibular response has reached a ceiling for which it can no longer compensate for disparities at the neuromuscular level due to the addition of a cognitive task. It is also possible a separate mechanism is modulating the balance response, as there are no differences in AP postural sway between age groups or cognitive-task conditions. Older adults experience a reorganization of spinal and cortical control of posture, with increase in cortical activation and decreases in cortical inhibition (Papegaaij et al., 2014). Therefore, it is possible that an increase in excitability of the cortex could have induced the observed postural response in the older women.

The efficacy of a dual-task experimental paradigm can be affected by several factors, including the difficulty of the motor and secondary cognitive task, as well as each participant's individual comfort-level regarding either task. Therefore, the primary limitation of the present protocol was the diverse ranges of comfort while performing mental arithmetic. Participants who felt more at ease with the math-based task may have diverted fewer cognitive resources to the task than those who were uncomfortable performing math. Additionally, the continuity of the cognitive task was irregular, as some participants were able to answer quickly within the 10-s interval. Therefore, these participants may not have been under true dual-task conditions for the entirety of the trial. Future studies would benefit from a continuous cognitive task or by recording the participants' response time and utilizing data during true dual-task conditions.

Conclusion

The present findings depict augmented vestibular-evoked balance responses in older females compared with young, as well as during dual-task conditions in the young. These modulations could be controlled via age-related increases in sensitivity of the vestibular nuclei, or perhaps with increased cortical excitability. It seems as though there are multiple mechanisms involved in modulating, and perhaps also compensating, for age-related discrepancies in sensory inputs or from diverted cognitive resources. The observed adjustments in the vestibular-evoked balance response from the current study may indicate vestibular involvement in the instability often experienced in older adults during standing balance.

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