Cognitive Compensation Among Older Adults in the Context of an Unpredictable Platform Perturbation

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Abstract

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Research has revealed an increasing interdependence between cognitive and both auditory and motor functioning with age (Baltes & Lindenberger, 1997) with correlational work suggesting an association between hearing loss and falls (Viljanen et al., 2009). The current study was designed to experimentally investigate cognitive capacity as a candidate underlying this association. Twenty-nine younger adults (*M* = 21.83, *SD* = 3.01) and twenty-five older adults (*M* = 65.32, *SD* = 3.26) were recruited to balance in response to a platform perturbation and perform a cognitive task alone and concurrently. These tasks were also completed in noisy conditions to simulate age-related hearing loss. We hypothesized that older adults would show greater dual-task costs than younger adults and that performance costs would be exacerbated by attentional load (i.e., dual-tasking) and auditory challenge (i.e., noise). It was also hypothesized that older adults would prioritize balance over cognitive performance. Results revealed that cognitive performance was negatively impacted by age and noise but not by attentional load, with the effect of auditory challenge exacerbated among older adults. Postural data was analyzed for a subset of thirteen younger (*M* = 22.54, *SD* = 2.50) and thirteen older (*M* = 65.31, *SD* = 4.05) adults. While differences were found in response to task manipulations in both the reflexive and voluntary portion of the response among younger adults, older adults demonstrated a conservative response suggesting postural prioritization. These findings

complement epidemiological work linking hearing loss and mobility decline, and are novel in providing experimental evidence that implicates cognitive capacity as an underlying factor.

Table of Contents

Cognitive Compensation among Older Adults in the Context of an Unpredictable Platform Perturbation

As the number of Canadian Seniors is projected to increase from 4.2 to 9.8 million between 2005 and 2036 (Statistics Canada, 2006), research on healthy aging is gaining momentum. With age, older adults experience increasing difficulty with cognitive, physical and sensory functioning, which in turn affects social functioning and impacts independent living. Recent research has demonstrated a role for cognition in both hearing and balancing with this interdependence increasing with age (e.g., Baltes & Lindenberger, 1997; Schneider, Pichora-Fuller, & Daneman, 2010; Shumway-Cook & Wollacott, 1999). Furthermore, epidemiological work suggests a correlation between hearing loss and falls, with poorer hearing acuity associated with an increased risk of falls (Viljanen et al., 2009). Researchers suggested that this association could be explained by social withdrawal and eventual deconditioning due to reduced out-of-home activity, or through shared pathology affecting both auditory and vestibular systems (Viljanen et al., 2009). An alternative explanation is that with age, both auditory functioning and balance increasingly rely on cognitive resources to compensate for peripheral changes (Li & Lindenberger, 2002). However, despite the accumulating correlational evidence, little experimental research exists investigating this association. Therefore the present study was designed to explore the underlying mechanism with the aim of informing geriatric practice and rehabilitation. Literature on auditory and motor aging will first be reviewed, followed by a consideration of the intersection between these two domains and theoretical implications.

Auditory aging

With age, hearing can be impacted by several age-normative changes including both peripheral and cognitive factors such as general declines in cognitive performance and changes in more central-auditory processes which may contribute to hearing difficulty (Martin & Jerger, 2005; Pichora-Fuller, Schneider, & Daneman, 1995; Schneider et al., 2010). One obstacle faced by many older adults is hearing loss in the form of presbycusis, or age-related hearing loss in the high frequency range. Presbycusis is found among 6.4% of Canadians aged 55-64; 12% aged 65-74, and 26% of those aged 75 years and older (Statistics Canada, 2006). In addition to presbycusis, aging is associated with losses in spectral and temporal acuity, and losses of neural synchrony in the auditory pathways. Provided that these deficits are not too severe and that the signal level of a stimulus is sufficient, these changes have little to no effect in quiet contexts. However, many older adults report difficulty following conversation in multi-speaker contexts and in environments with background noise. This effect is exacerbated by a fast rate of speech or speech that is high in grammatical complexity (Schneider et al., 2010). Although hearing loss may account for speech-recognition difficulties in quiet conditions, peripheral changes in the auditory system can only account for a portion of the difficulties experienced by older adults in noisy situations.

To fully comprehend an auditory scene, listeners must locate and perceptually segregate the sound sources in their environment in order to focus their attention on target sources and ignore the processing of information from irrelevant sources. This process is facilitated when the spectral differences between sources are incongruent (Brungart, Simpson, Ericson, & Scott, 2001), when the harmonic structure between two sources differs (Alain, Dyson, & Snyder, 2006; Alain, McDonald, Ostroff, & Schneider, 2001) and when sounds are spatially separated (Freyman, Helfer, McCall, & Clifton, 1999). Once the auditory scene has been separated into sound sources, listeners are better able to focus their attention on target information and suppress information from competing speakers in order to prevent perceptual or informational masking (i.e., the intrusion of irrelevant information; Freyman et al., 1999; Schneider & Daneman, 2007).

In addition to locating speakers in space and focusing attention on relevant information, speech comprehension is affected by temporal processing, partly under the control of the central auditory nervous system. Since speech is a complex sound varying over time, listeners must process brief, time-varying acoustic information to understand individual phonemes, process rapid acoustic information about individual phonemes in a sequence of changing acoustic cues, and follow the overall timing of a spoken message (Gordan-Salant, Fitzgibbons, & Yeni-Komshian, 2011). With age, processing time and inter-aural timing are affected, with the auditory system becoming slower and more asynchronous, respectively (Pichora-Fuller, 2003).

Cognitive theorists have suggested that in addition to signal degradation from a deteriorating peripheral auditory system, older adults may be more vulnerable to intrusions from irrelevant or distracting stimuli than younger adults due to age-related changes in cognitive functioning such as changes in working memory (Brebion, 2003; DeDe, Caplan, Kemtes, & Waters, 2004; Tun, Wingfield, & Stine, 1991;Van der Linden et al., 1999), slowed speed of processing (Stine, 1995; Stine & Hindman, 1994; Tun, Wingfield, Stine, & Mecsas, 1992; Wingfield, Poon, Lombardi, & Lowe, 1985) and a deficit in inhibition (Hasher & Zacks, 1988; Hasher, Zacks, & May, 1999). To this end, the association between cognitive and auditory aging has become an area of interest with researchers implementing epidemiological, experimental and clinical approaches to investigate the link. Support for this association can be found in studies suggesting that hearing loss is independently associated with lower scores of memory and executive functioning (Lin et al., 2011; Lin, 2011) and that hearing loss is independently associated with an increased risk of cognitive decline and incident dementia (Lin et al., 2013).

In addition to epidemiological studies, researchers have also experimentally investigated the interaction between cognitive aging and hearing in studies of speech perception by manipulating sensory load, for example simulating aspects of age-related hearing loss by overlaying target speech with background noise such as multi-speaker babble. In studies of speech perception older adults derived more benefit from contextual cues in the sentences presented when compared to younger adults under high noise conditions, thus suggesting a compensatory cognitive process (Pichora-Fuller et al., 1995). Other facilitative compensatory mechanisms include active listening whereby listeners are instructed to direct their attention to a stimulus (Alain, McDonald, Ostroff, & Schneider, 2004) and when cues are provided for source segregation (Humes, Lee, & Coughlin, 2006) although older adults do not benefit as much from auditory cues as their younger counterparts (Murphy, Daneman, & Schneider, 2006).

Importantly however, this utilization of top-down resources in speech perception may come at cost to other cognitive processes. When auditory memory stimuli are presented in noise, age and noise exhibit similar negative effects on long-term memory. One potential explanation of the results is that a decrease in processing resources with age is associated with less effective encoding of information into secondary memory (Rabbitt, 1968, 1991; McCoy et al., 2007; Murphy, Craik, Li, & Schneider, 2000; Suprenant, 1999, 2007). Similarly, when speech is accelerated to challenge processing speed requirements, age, hearing loss, and accelerated speech are more detrimental in syntactically complex sentences than in simple ones. Therefore there is a role for both age-related changes in hearing acuity and cognition in the comprehension of speech, especially when a threshold of processing difficulty has been breached (Wingfield, McCoy, Peelle, Tun, & Cox, 2006).

Another experimental strategy used to examine the cognitive contribution to hearing in old age is the dual-task paradigm. In this approach, age-related reductions in cognitive capacity are simulated using a concurrent, or secondary, task. Participants are administered both tasks separately (i.e. single-task conditions) and simultaneously (i.e., dual-task condition) with the premise being that if both single tasks are competing for a common limited resource then completing both tasks together will result in a deficit in performance in one or both tasks. Dual-task costs are defined as a drop in performance from single-task to dual-task conditions. To this end, performing a simultaneous secondary task in a non-auditory modality produced the same effect on memory as continuous babble, further supporting the notion that babble requires the listener to divert attentional resources to extract the signal from background noise, thus leaving fewer resources for higher level information processing (Heinrich, Schneider, & Craik, 2008). Researchers have also demonstrated that dual-task costs are exacerbated by aging and hearing loss during performance of an auditory recognition task (Gosselin & Gagné, 2011; Tun, McCoy, & Wingfield, 2009). Such a pattern suggests that older adults recruit more cognitive resources to perform the listening task at a cost to the concurrent task, thus rendering the listening task more effortful.

Recent neuroimaging studies complement the behavioural and experimental work. Smaller global and regional brain volumes have been observed in older adults with hearing loss compared to age-matched controls (Lin et al., 2014; Lin et al., 2013). Functional neuroimaging during speech perception offers more direct evidence of cognitive recruitment for hearing. In fMRI studies of sentence comprehension and word identification (Wingfield & Grossman, 2006; Wong et al., 2009), older adults showed less activity in regions associated with sensory analysis, but greater activity in regions associated with working memory and attention compared to young adults. This neural pattern of cognitive compensation is exaggerated when background noise is added. Furthermore, increased cortical activity in general cognitive regions was associated with performance on word accuracy and speech comprehension among older adults, suggesting a compensatory strategy wherein cognition is utilized to compensate for hearing difficulty.

In more clinically oriented approaches, among those older adults diagnosed with hearing impairment, cognitive scores (i.e., working memory, general intelligence) correlated with scores on speech tests even after amplification with hearing aids (Pichora-Fuller, 2009). Furthermore, among first time hearing aid users, higher baseline cognitive scores were associated with an increased performance on a speech recognition task in noise when performed with amplification devices (Gatehouse, Naylor, & Elberling, 2003, 2006; Lunner, 2003).

In sum, older adults experience both peripheral and central changes to their auditory systems, which influence speech perception, particularly in noisy conditions. Epidemiological, experimental, and clinically focused research suggests a role for top-down cognitive processes such as greater utilization of sentence context, and increased attentional allocation in old age.

Motor Aging

In addition to auditory aging, older adults also experience changes in motor functioning, which contribute to frailty and disability. Such declines may also have a negative impact on older adults' ability to perform functional activities of daily living (Seidler et al., 2009) and participate in social activities outside the home (Rosso, Taylor, Tabb, & Michael, 2013). Some of these changes can be linked to physical causes such as sarcopenia, a reduction in muscle mass and strength that occurs normatively in old age (i.e., hip abductor, quadriceps; Lauretani et al., 2003). Essentially, the force produced by a muscle contraction decreases as a result of an age-related reduction in the number of muscle fibers, cross-sectional area of the muscle or reduced voluntary activation. This diminished muscle strength in turn affects proprioception or the conscious or unconscious awareness of body position, movement and forces acting on the body (Hurley, Rees, & Newham, 1998). Further age-related changes include decreases in joint flexibility (i.e., ankle; Nolan, Nitz, Choy, & Illing, 2010).

These changes in physical status subsequently impact aspects of mobility such as gait, static and dynamic balance, and falls risk. Gait among older adults is typically assessed by measuring parameters such as segment position and joint angle, stride variability, and speed during overground walking, treadmill walking, and obstacle avoidance tasks. Older adults typically exhibit greater gait variability, decreased walking speeds (Callisaya, Blizzard, Schmidt, McGinley, & Srikanth, 2010), shorter stride lengths, decreased stride frequency and a more rigid posture (Kovacs, 2005) compared to young controls. When ambulating around and over obstacles, older adults typically exhibit one of two patterns: change direction and move away from the obstacle or step over the obstacle by changing the limb trajectory (Patla, Prentice, Robinson, & Neufeld, 1991). Further accommodations include taking shorter steps in challenging environments (Medell & Alexander, 2000) and adopting a more conservative gait (e.g., slower speed; Hseih-Ching, Ashton-Miller, Alexander, & Schultz, 1991).

In addition to gait changes, older adults exhibit changes in balance and postural stability, which can manifest when standing (i.e., static) and/or when responding to an environmental event such as a platform movement (i.e., dynamic). During upright stance, maintaining balance requires an individual to keep their centre-of-mass (COM) within the limits of their base-of-support by shifting the foot centre-of-pressure (COP). With aging, upright postural sway increases (Peterka, Black, & Schoenhoff, 1990) and has been linked to subsequent falls (Maki, Holliday, & Fernie, 1990). When encountering dynamic postural challenges such as an unpredictable platform movement (i.e., perturbation), individuals must produce appropriate motor responses in order to maintain their COM over their base of support using ankle (i.e., rotating body around ankle joints) or hip (i.e., flexion or tension at the hips) strategies for example (Horak, Shupert & Mirka, 1989; Maki & McIllroy, 1996). When challenged with an unpredictable platform perturbation, older adults generate a greater centre of mass (COM) sway (Tsai, Hiseh, & Yang, 2014) and are more likely than their younger counterparts to step during a perturbation to maintain balance and initiate stepping at lower perturbation magnitudes (Jensen, Brown, & Woollacott, 2001).

In the last decade, researchers have conceptualized balance and gait as less automatic and spinally mediated than before (Woollacott & Shumway-Cook, 2002). Accordingly, there has been an increase in the specificity of cognitive functions associated with postural control and gait where experimental studies have examined correlates of walking performance, either performed alone or paired with a concurrent task to simulate age-related reductions in cognitive capacity (i.e., the dual-task method). For example, in a sample of non-demented older adults, measures of executive functioning and memory correlated positively with gait speed (Ble et al., 2005; Holtzer, Verghese, Xue, & Lipton, 2006). Similarly, dividing participants into low and high performance on measures of executive functioning predicted stride time variability on a routine walking task (Hausdorff, 2004) and lower levels of cognitive functioning correlated with the risk of developing a mobility impairment (Buchman, Boyle, Leurgans, Barnes, & Bennett, 2011).

In keeping with other age-simulation work, reduced sensory inputs have been examined in the context of balance and walking. For example, altering proprioceptive input by balancing on a compliant surface or restricting vision while balancing is more detrimental to older adults' balance than young adults' and these effects are further exacerbated by the addition of a cognitive load or a history of falls (Shumway-Cook & Woollacott, 2000; Shumway-Cook, Woollacott, Baldwin, & Kerns, 1997; Teasdale, Bard, Larue, & Fleury, 1993). Other researchers have experimentally paired cognitive and balance tasks to determine what task demands might influence the association between mobility and cognitive functioning. In such studies older adults demonstrated increased postural sway in upright stance (Maylor & Wing, 1996) and a greater drop in performance on measures of memory and walking (i.e., obstacle avoidance) under dual-task conditions

(Chen et al., 1996; Lindenberger, Marsiske, & Baltes, 2000). Similarly, in postural recovery studies involving unpredictable platform movements, older adults have exhibited greater dual-task costs in terms of cognitive performance and/or postural recovery, particularly in the later less automatic stages of the postural response (Brown, Shumway-Cook, & Woollacott, 1999; Norrie, Maki, Staines, & McIllroy, 2002; Rankin, Wollacott, Shumway-Cook, & Brown, 2000).

However, unlike dual-task research on auditory perception, in some instances the addition of a concurrent cognitive task is facilitative. Particularly for older adults, balancing or walking paired with a simple task may improve motor performance, but these benefits turn into costs as the task increases in complexity (Huxhold, Li, Schmiedek, & Lindenberger, 2006; Lövdén, Schaefer, Pohlmeyer, & Lindenberger, 2008; Verrel, Lövdén, Schellenbach, Schaefer, & Lindenberger, 2009). One interpretation of this nonlinear pattern is that a simple task facilitates performance, as directing full attention to a highly automated process of walking or balancing is unnatural and detracts from motor coordination. However, at higher levels of cognitive challenge, the benefit is attenuated due to resource competition (Huxhold et al., 2006).

In addition to cognitive challenge, fear of falling plays a role in motor dual-task studies, often leading older adults to allocate more attention to maintaining posture than to a concurrent cognitive task under dual-task conditions. Postural prioritization is commonly expressed as greater dual-task costs in the cognitive than the motor domain, and increases with postural threat (Li, Lindenberger, Freund, & Baltes, 2001; Kemper, Herman, & Lian, 2002). Postural prioritization can also be observed in dual-task situations that allow free access to assistive devices: When given a choice of compensatory aids, older adults chose to maximize walking performance whereas younger adults optimized cognitive performance (Li et al., 2001).

Beyond walking speed and cognitive performance, more temporally sensitive measures of muscle activity using electromyography (EMG) or brain activity using electroencephalography (EEG) allow for a finer examination of moment to moment fluctuations in attentional allocation between two tasks (e.g., Quant, Adkin, Staines, Maki, McIlroy, 2004). Very recently portable neuroimaging devices (i.e., functional near-infrared spectroscopy) have generated evidence showing prefrontal regions are more involved in walking while talking compared to walking alone and that this activity is attenuated with age, suggesting that older adults underutilize the prefrontal cortex to coordinate and monitor challenging locomotor situations (Holtzer, Mahoney, Izzetoglu, Onaral, & Verghese, 2011). Furthermore, postural reactions to unexpected platform movements appear to be slowed or weakened with aging as measured by neural activity (Maki & McIlroy, 2007).

Findings from clinical populations provide convergent evidence for the link between cognition and mobility wherein older adults who stop walking while talking are at a higher risk for falls (Lündin-Olssen et al., 1997) and individuals with a diagnosis of Parkinson's or Alzheimer's disease demonstrate more gait abnormalities when performing a simultaneous cognitive and walking task (Yogev-Seligmann, Hausdorff, & Giladi, 2008). Others have reported that computerized dual-task training enhanced balance and mobility (Li et al., 2010). Similarly, computerized brain training slowed the degradation of balance, improved gait while distracted, and increased walking speed in single and dual-task conditions (Smith-Ray et al., 2013; Verghese, Mahoney, Ambrose, Wang, & Holtzer, 2010).

In sum, the current state of knowledge in the area of mobility and aging indicates a strong link between cognition and mobility in old age, as shown in correlational, experimental dual-task, neuroimaging and intervention studies. Like auditory aging, competition for limited cognitive capacity increases as a function of multiple factors such as motor complexity, fear of falling, and cognitive complexity.

Comorbidity of Hearing Loss and Poor Mobility

In addition to the growing body of research demonstrating that hearing and mobility are each correlated with cognitive functioning, emerging research suggests an association between hearing loss and mobility decline (Viljanen et al., 2009). This age-related increase in interdependence between sensory and motor functioning was supported by data from the Finnish Twin Study on Aging, wherein seniors with poorer hearing acuity also had a higher risk of falls after the effects of environment and genetics were controlled (Viljanen et al., 2009). The authors suggested that this link between hearing and mobility may arise from social withdrawal and eventual deconditioning due to reduced out-of-home activity. Another proposed pathway is through shared cochlear and vestibular pathology as both the hearing (i.e., cochlea) and vestibular (i.e., labyrinth) organs are anatomically closely localized, share fluid-filled bony compartments and blood circulation, are both served by the eighth cranial nerve and have similar mechanosensory receptor cells, which detect sound, head movements and orientation in space (Viljanen et al., 2009). However, controlling for vestibular function did not substantially change the magnitude of the association between hearing loss and falls in a study of young adults and older adults (Lin & Ferrucci, 2012).

Another possible explanation for the link between hearing and mobility decline, and the basis for the present study, is that because both hearing and motor performance require greater cognitive capacity in aging, there is competition for compensatory cognitive resources, which are themselves diminishing. Evidence for this increasing interdependence between sensory, sensorimotor and cognitive functioning with age stems largely from the separate bodies of research reviewed above. Consideration of auditory, cognitive, and motoric aging within the same study is much less common. One exception to this comes from the population-based findings from the Berlin Aging Study (BASE: Lindenberger & Baltes 1994; Lindenberger & Ghisletta, 2009). This was a multidisciplinary longitudinal investigation of older adults, in which a link between cognition and both sensory abilities and gait/balance was demonstrated. Very old participants were assessed on balance and gait, visual and auditory acuity, and multiple domains of cognitive functioning. Cross-sectional analyses revealed that age-related variance in general intellectual functioning was accounted for by visual (distance) acuity (64.5%), auditory pure-tone acuity (74.5%), and balance/gait (82.6%). In contrast, markedly lower values were found in a comparison sample of young and middle-aged adults (Baltes & Lindenberger, 1997) suggesting a progressive "dedifferentiation" between peripheral and central processes in later life due to a general factor or "Common Cause". More recent examination of the longitudinal BASE findings (Lindenberger & Ghisletta, 2009) suggests that such a general factor accounts for less of the longitudinal relationship between sensory-motor and cognitive performances, and that a more immediate mechanism such as cognitive compensation might account for the remaining age-related variance.

The concept of cognitive compensation has been widely adopted in several models of sensory and cognitive aging (for reviews, see Li & Lindenberger, 2002; Schneider & Pichora-Fuller, 2000). Sometimes referred to as the *Shared Resource*, *Integrated System, or Cognitive Compensation* view, the general perspective assumes that the increasing interdependence between sensory-motor and cognitive abilities stems from a progressive limitation on resources and possible compensatory reallocation (Schneider & Pichora-Fuller, 2000). Within this view, declines in cognitive capacity would impact performance on auditory and motoric tasks and vice versa. Simulations of age-related loss, in which increasing sensory load results in reductions to cognitive performance, support the shared resource view. Similarly, when cognitive load is increased by increasing task complexity or by adding a concurrent task, there is a cost to perceptual or motor performance. Furthermore, across most studies the negative impact seems to be greater for older rather than younger adults suggesting competition for scarce resources and compensatory tradeoffs (Li & Lindenberger, 2002).

A neural extension of cognitive compensation has been proposed by Park and Reuter-Lorenz (2009) in their *Scaffolding Theory of Aging* (STAC) which states that older adults maintain a relatively high level of performance despite neural challenges and functional deterioration associated with age by engaging in compensatory scaffolding via the recruitment of additional neural circuitry (Park & Reuter-Lorenz, 2009). The *STAC* model is based on evidence demonstrating that with age, there are changes at both the structural and neurobiological levels, which are compensated for by functional changes in the aging brain. These changes may occur in the form of altered connectivity and organization at the local and global levels as well as by increased co-activation of posterior and frontal brain regions, or of homologous regions in the opposite hemisphere (Cabeza, 2002; Goh, 2011).

Following the *Cognitive Compensation* approach, Li and colleagues have extended these ideas to the realm of ecologically valid measures of complex processing, stating that the pattern of compensation and task emphasis should vary according to the ecological relevance of any given task. In the context of cognitive-motor dual-tasking, the objective risk and subjective fear of falling associated with walking or balancing would likely outweigh the importance of maintaining optimal cognitive task performance. Given the more serious consequences of falling for older adults, one would expect them to allocate more of their cognitive resources to maintain stability at a cost to concurrent cognitive task performance (Li, Krampe, & Bondar, 2005; Li & Lindenberger, 2002). This pattern of prioritization has been termed the “posture first” response, and has been used to interpret age differences in motor dual-task performance. For example, in cognitive-motor dual task studies, older adults have shown greater cognitive dual-task costs than young adults, but no age difference in motor dual-task costs (Li et al., 2001). Others have found that manipulations of task difficulty lead to declines in motor performance (e.g., postural stability) in young adults but not in older adults, whereas cognitive declines are more pronounced for the older adults (e.g., Lajoie, Teasdale, Bard, & Fleury, 1993).

To date, researchers have demonstrated the association between hearing and aging, mobility and aging, and cognition and aging, in largely separate studies that are correlational in nature. However, despite robust correlational evidence, little experimental evidence exists investigating the hearing-mobility link and its underlying mechanism.

Current Study

The purpose of the current study is therefore to experimentally integrate the domains of auditory and motor functioning to better understand their correlation. A dual-task method was used to challenge younger and older adults in both hearing (i.e., auditory cognitive task) and motor (i.e., balance) domains. In line with the Cognitive Compensation approach, we paired a challenging auditory working memory task with a postural recovery task (response to an unpredictable platform movement), expecting that older adults would show disproportionately greater dual-task costs than young adults due to competition for scarce cognitive resources that could be allocated to maintain either cognitive or motor performance. Listening difficulty was also manipulated by adding background noise to the auditory stimuli. This allowed a simulation of auditory challenge similar to the effects of auditory aging. As such, we expected that under noisy listening conditions, young adults would resemble older adults in their allocation of cognitive resources. Finally, in line with the posture first principle, we anticipated that older adults would prioritize balance performance over cognitive performance due to the ecological value of balancing, whereas young adults would be able to more flexibly distribute their attentional resources between the auditory task and the balance task.

Method

Participants

The total sample consisted of fifty-four individuals: twenty-nine healthy younger adults (YA) between the ages of 18 and 30 years old (*M* = 21.83, *SD* = 3.01, females = 24) recruited through the Concordia University participant pool, and twenty-five healthy older adults (OA) between the ages of 65 and 85 years old (*M* = 65.32, *SD* = 3.26, females = 19) recruited through an existing senior participant pool at Concordia and advertisements in a local senior paper. Younger adults received course credits and older adults received a seventy-dollar research honorarium for approximately five hours of participation over two sessions. Exclusion criteria included the existence of any progressive medical conditions and the use of any medication affecting cognitive or balance abilities (i.e., anti-anxiety medications, muscle relaxants, etc.). Further exclusion criteria included suspected presence of mild cognitive impairment as defined by the Montreal Cognitive Assessment (MoCA < 26/30; Nasreddine et al., 1996), auditory impairments beyond normative age related hearing loss (i.e., average pure tone hearing threshold > 25 dB, hearing aid) and any self-reported difficulties in balance or mobility. Participants were also required to have English as their first language and have normal or corrected-to-normal vision.

Materials

Participants were administered a series of background measures to assess sensory, motor and cognitive functioning and to obtain additional demographic and health information (Session One). Balance and cognitive performances were assessed independently using an experimental dual-task method in a second session.

Background measures. The **Demographic Questionnaire** consists of a 42-item questionnaire used to obtain background information such as the participants' chronological age, years of education, and general health status (see Appendix A).

The **Montreal Cognitive Assessment "MoCA"** (Nasreddine et al., 1996) is a 30-point clinical screening test designed to detect mild cognitive impairment in older adults ($\alpha = 0.83$, test-retest reliability = 0.92; Nasreddine et al., 2005). Visuo-spatial abilities were assessed using a clock-drawing task and a three-dimensional cube copy. A short-term memory recall test involved two learning trials of five nouns and recall at the end of the test. Executive functions were assessed by a trail-making B task, a verbal fluency task, and a two-item verbal abstraction task. Attention and vigilance were evaluated using a target detection tapping task, a serial subtraction task, and digits forward and backward task. Language was assessed using a three-item naming task with low-familiarity animals (lion, camel, rhinoceros), and repetition of two complex sentences. Finally, orientation to time and place was evaluated. The subtest scores were then summed with a score of 26/30 or greater indicating normal cognitive performance. One point was added to the total score for those with 12 years or less of education.

The **Coding (Digit Symbol) Task** (Wechsler, 2008) is a clinical subtest of the Wechsler Adult Intelligence Scale (WAIS-IV) that assesses cognitive processing speed ($\alpha = 0.90$; Wechsler, 2008). This test consists of nine digit-symbol pairs (e.g. 1/-, 2/⊥ ... 7/Λ, 8/X, 9/=) followed by a list of randomly ordered digits. Participants were asked to write down the corresponding symbol under each number as quickly as possible. The final score corresponded to the number of correctly written symbols within the allotted time of 120 seconds.

The **Letter Number Sequencing Task** (Wechsler, 2008) is a clinical subtest from the WAIS-IV used to assess working memory (α = 0.81; Wechsler, 2008). The task consists of 21 sequences of letters and numbers (ranging from two to nine letter-number combinations) verbally presented to the participant. Participants were asked to first repeat the numbers in ascending order followed by the letters in alphabetical order (e.g., present with 9-L-2-A, the correct response is 2-9-A-L). Three trials were presented per span length and the participant advanced to longer spans if they got at least one trial correct (one of three possible points). The test was terminated once the participant failed three trials at the same span length. The final score corresponded to the highest span length correctly repeated.

The **Delis Kaplan Executive Functioning Scale "D-KEFS" (Trail Making Test) (**Delis, Kaplan, & Kramer, 2001) is used as a measure of executive functioning including flexibility of thinking, inhibition, problem solving, planning, impulse control, concept formation, abstract thinking, and creativity. This scale consists of nine subtests that can be used in conjunction or as stand-alone tests. For the present study, only the Trail Making subtests were utilized, which consist of a visual cancellation task and a series of connect-the-circle tasks (test-retest reliability = 0.38-0.77; Delis, Kaplan & Kramer, 2001). The score for each task is a measure of completion time (seconds). According to the authors, the primary executive function task is condition four: Number-Letter Switching, which is meant to assess flexibility of thinking on a visual-motor sequencing task. The other four conditions of this test allow the examiner to gain information regarding an examinee's ability at component skills including visual scanning, number sequencing, letter sequencing, and motor speed. The final score was the number of seconds taken to complete each condition.

The **Dynamic Gait Index "DGI"** (Shumway-Cook & Woollacott, 1997) is used as a global measure of mobility in older adults. This scale consisted of eight tasks scored on a 4-level ordinal scale (3 = normal, 2 = mild impairment, 1 = moderate impairment, and 0 = severe impairment) based on visual observation. Participants are instructed to walk at different speeds, walk with cued head turns, ambulate over and around small obstacles, ascend and descend stairs, and to make quick turns while walking. The maximum possible score on the DGI is 24 and scores of 19 or less have been related to increased incidence of falls in the elderly (Shumway-Cook & Woollacott, 1997).

The **Sit-to-Stand** (Puthoff, 2008). The Sit-to-Stand (test-retest reliability = 0.89; Tiedemann, 2008) is a timed test of mobility wherein participants are asked to stand up five times from a seated position with their arms crossed as quickly as possible. The score is the time (seconds) it took for the participant to complete all five repetitions of the task. Completion time was then classified into one of four categories with scores > 3 indicating risk of frailty (Buatois, et al., 2008).

The **Activities-Specific Balance Confidence Scale "ABC Scale"** (Powell & Myers, 1995). The ABC Scale is a 16 item self-report measure ($\alpha = 0.96$; Huang & Wang, 2009; test-retest reliability = .92; Powell & Myers, 1995) intended to assess confidence in balance on a 0 (i.e., no confidence) to 100% (i.e., complete confidence) scale in performing activities such as walking up and down stairs or walking in a crowded area varying in level of difficulty. Participants were asked to rate their confidence using any supports (i.e. handrail, walker) typically utilized. A summary score was derived by averaging the percent confidence over the 16 items.

Pure-tone audiometry. A Maico (MA 42) audiometer was used to assess participants' hearing ability by establishing an absolute threshold of detecting pure tones. Participants were presented with pure tones at varying frequencies and intensities over headphones and indicated that a tone was detected by pressing a hand-held buzzer. A first tone was administered at 1000Hz at 40dB in the participants' right ear. The decibel (dB) level presented was gradually reduced by increments of 10 dB until the lowest tone the participant was able to perceive 50% of the time was determined. This procedure was repeated for frequencies of 250 Hz, 500 Hz, 2000 Hz, 3000 Hz, 4000 Hz and 8000 Hz. This same protocol was administered for the left ear. The mean absolute threshold of hearing corresponded to the average of the minimum tone detection thresholds assessed across all frequencies presented to both ears (see Appendix B).

The **Listening Self Efficacy Questionnaire "LSEQ"** (Smith, Pichora-Fuller, Watts, & La More, 2011). The LSEQ quantifies listening self-efficacy, or the confidence of a listener regarding their capacity to successfully listen, where the goal is for the listener is to understand speech. The LSEQ is comprised of eighteen questions ($\alpha = 0.80$; Smith et al., 2011) wherein participants were asked to rate their self-efficacy on a scale of 0 (i.e., cannot do this at all) to 100 (i.e., I am certain I can do this) percent in a variety of listening situations (i.e., I can understand the TV, I can understand conversation when someone speaks in a whisper) at the given moment without the use of listening aids such as hearing aids. A summary score was derived by averaging the percent confidence across the eighteen items.

Early Treatment Diabetic Retinopathy Study "ETDRS" eye chart (Early Treatment Diabetic Retinopathy Study Research Group, 1985). The ETDRS was administered to assess distance visual acuity, and requires participants to identify and verbalize letters from a standard eye chart from a distance of twenty feet. Participants were asked to cover their left eye with one hand and report the letters in each row, starting with the top row (i.e., biggest letters) and working down to the lowest row (i.e., smallest letters). This procedure was repeated with participants covering their right eye. The smallest letter a participant could identify indicated their visual acuity (M-unit).

Additional questionnaires addressing psychosocial functioning were also administered but will not be discussed for the purpose of the present paper.

Experimental measures. The **perturbation platform**. The Concordia University PERFORM Center Posture and Movement Laboratory (PML) is equipped with a custom-made by H2W perturbation platform capable of delivering perturbations in both the horizontal and rotation (yaw) directions. The platform also consists of two force plates (AMTI, based on the OR6-6-2000 model) bolted to a platform, which function to measure center of pressure (COP) fluctuations as an index of postural sway at a frequency of 1000 Hz. During a perturbation the platform was programmed to move forward a distance of 50 mm at a maximum velocity of 150 mm/s and an acceleration of 500 mm/s^2 (Quant et al., 2004). This distance and velocity were chosen to be very mild, similar to the experience of balancing in a moving bus.

Motion capture system (Vicon, MX-T20 system). The motion capture system was used to measure 3-dimensional positioning of major landmarks on the body (i.e., legs, chest, arms, head) using a standard whole-body 35 marker placement protocol (Plug-in Gait, n.d; see Appendix C). The reflective markers were attached to participants to allow for 8 high-speed infrared cameras to capture kinematic data at a frequency of 100 Hz by measuring joint angle displacement following a platform movement. The derived kinematic data were used to generate center of mass parameters commonly used to characterize postural sway and recovery.

Electromyography "EMG" (Noraxon, TeleMyo 2400T). The EMG system uses 16 bipolar surface electrodes to record the amplitudes and peak latencies of muscles responses via small electrical potentials recorded from the muscle at a frequency of 1500 Hz. Electrodes were placed on muscles relevant to postural control such as the tibialis anterior (i.e., shin) and gastrocnemius (i.e., calf) in order to measure the latency of muscle contractions (mV) following a platform movement (see Appendix D). For the purposes of the present report, EMG data will not be discussed further.

The auditory working memory "***n*-back"** task (Kirchner, 1958). The *n*-back task is a measure of working memory. More specifically, participants are presented with a series of fifteen randomly ordered single digit numbers between one and ten with the exclusion of the two-syllable numeral seven (without consecutive repetition). A trial is defined as one sequence of fifteen digits. In the present experiment, the stimuli were presented via insert headphones (Genieaudio E-A-RLINK 3A) at 50 dB greater than each participant's average absolute hearing threshold, as determined by pure-tone testing in Session One. Participants were asked to repeat the number presented *n* steps before (1-back) while the tester recorded their verbal responses. Half the trials were presented in background noise (i.e., multi-speaker babble consisting of the sound of six people speaking simultaneously and unintelligibly) at a fixed signal-to-noise (SNR) ratio of -6 dB. Noise was induced to simulate age-related hearing loss. Cognitive performance was defined as the total number of correct responses (i.e., numbers) identified across a given trial (i.e., maximum of 14 correct per trial). The number of correct responses was then summed across all ten trials in a given condition (i.e., single-task quiet, single-task noise, dual-task quiet, dual-task noise) and converted into a percentage score (i.e., out of 100%).

Procedure

All participants were tested individually at the PERFORM Centre of Concordia University. Both younger and older participants completed testing in two sessions. In the first session, participants were instructed to carefully read and sign the consent form and complete the demographic questionnaire. They were then administered the background measures of cognition, mobility and audition. Younger participants completed all background tests except the MoCA and the DGI, as these measures are calibrated for older adults.

During a second session scheduled for a separate day approximately a week later participants completed the n-back cognitive and balance tasks under single and dual-task conditions. After being administered the ETDRS vision test, participants were weighed and measurements were taken (i.e., height, knee width, shoulder offset) for purposes of processing kinematic data. Examiners then applied electrodes and motion capture markers and fitted the participant with a safety harness. Following this protocol, participants were administered one practice trial of the cognitive task with a visual cue (i.e., numbers on a piece of paper) to ensure comprehension of the task followed by two practice trials (i.e., one in quiet; one in noise), which included feedback on performance after the completion of each trial. Participants completed one practice trial for the balance task. During the balance task participants were instructed to remain as stable as possible with their hands on their hips on the platform and look forward at a stationary target (7.5 x 12 x 2 cm) located 4.4 m away with one foot on each force plate hip width apart while it moved. During a 30 second trial, participants experienced zero, one, or two perturbations. Perturbations were timed in one of two time windows (i.e., the first 15 seconds or the second 15 seconds) and ordered randomly, with a minimum and maximum perturbation onset time of three seconds and twenty-seven seconds respectively. For trials with two perturbations, there was a minimum time constraint of five seconds between the first and second perturbation to allow for full recovery after the first. Three short beeps signaled the beginning of each trial and a single beep signaled the end of the trial. All participants received the same number of cognitive and balance practice trials.

Following practice, participants were administered blocks of five trials of the cognitive and balance tasks separately. Participants then completed the dual-task paradigm where the *n*-back and balance tasks were completed concurrently for ten trials, with a three minute break given after each group of five trials wherein participants were seated. Participants were asked to treat each task as equally important. The balance and cognitive tasks were then repeated again separately for five trials each to control for learning and fatigue effects. This entire sequence of trials was repeated in a noisy condition. The order of task (single task balance or single cognitive task) and auditory condition (quiet or noise) presentation was counterbalanced between participants (see Appendix E).

Data Analyses

Balance Data. Raw trajectory data collected via the markers (i.e., motion capture system) was filtered with a recursive low-pass Butterworth filter at 6 Hz in order to decrease background noise. The filtered data were then used to compute marker trajectory data in order to calculate the dependent variables of interest as detailed below (see Appendix F).

Total CoM Distance (mm). The total CoM distance was calculated by adding the total distance (mm) the participant traveled from CoM Onset, to the maximum CoM displacement (maximum displacement the person's CoM travels backward after the perturbation), to the minimum CoM displacement (the maximum displacement the person's CoM travels forward after the recovery from the perturbation). The CoM (center of mass) onset was defined as the time (s) at which the participant's CoM reached 10% of its maximum velocity. This is always a positive value since all values are taken as absolutes.

CoM Time-to-Maximum Displacement (s). The CoM Time-to-Maximum Displacement is the time from the perturbation onset until the participant reaches their maximum CoM displacement (backward movement). Perturbation onset is defined as the point at which the platform reached 5% of its maximum velocity, with velocity calculated using VICON motion capture markers placed on the four corners of the platform.

CoM Time-to-Peak (s). The CoM Time-to-Peak is the time from the perturbation onset until the participant reaches their minimum CoM displacement (forward movement).

Data Screening. A total of 30 older adult and 37 younger adult participants were screened for testing. Of those individuals screened, five older adults and eight younger adults were discontinued from testing because of low MoCA scores, an injury to a lower limb, scheduling conflicts, illness or hearing that surpassed the average pure tone threshold of 25 dB. Cognitive and balance parameter data was then checked for outliers (i.e., > 3.5 SD) both in terms of intra-individual and interindividual variability. One younger participant's data were not analyzed due to extremely high CoM Time-to-Peak scores on all four conditions.

Results

Means and standard deviations for all study measures are presented in Table 1. To examine group differences on the background measures, a series of independent samples *t*-tests were conducted. These tests revealed group differences on years of education, $t(48) = 1.51$, $p < .001$, where older adults had a greater number of years than younger adults. The groups also differed on their LSEQ scores, $t(52) = 2.17$, $p = .034$, with younger adults endorsing greater confidence in their listening capabilities compared with older adults. As expected, the two groups differed on their pure-tone thresholds where younger adults had lower thresholds compared to older adults, $t(52) = 1.16$, $p < .001$. Older adults also exhibited lower visual acuity in the right eye compared with younger adults, $t(51) = 1.16$, $p = .007$, and took longer to complete the Sit-to-Stand Task $t(52) = -4.41$, $p < .001$. The older adults performed significantly worse than the young adults on the Digit Symbol, $t(52) = 2.81$, $p = .007$, and both sequencing conditions of the DKEFS Trails, $t(51) = 14.86$, $p < .002$, $t(51) = 3.43$, $p = .016$. No statistically significant group differences were observed for the remaining baseline variables (ABC, LNS, LNS longest span, DKEFS Trails Condition Four).

Cognitive Accuracy

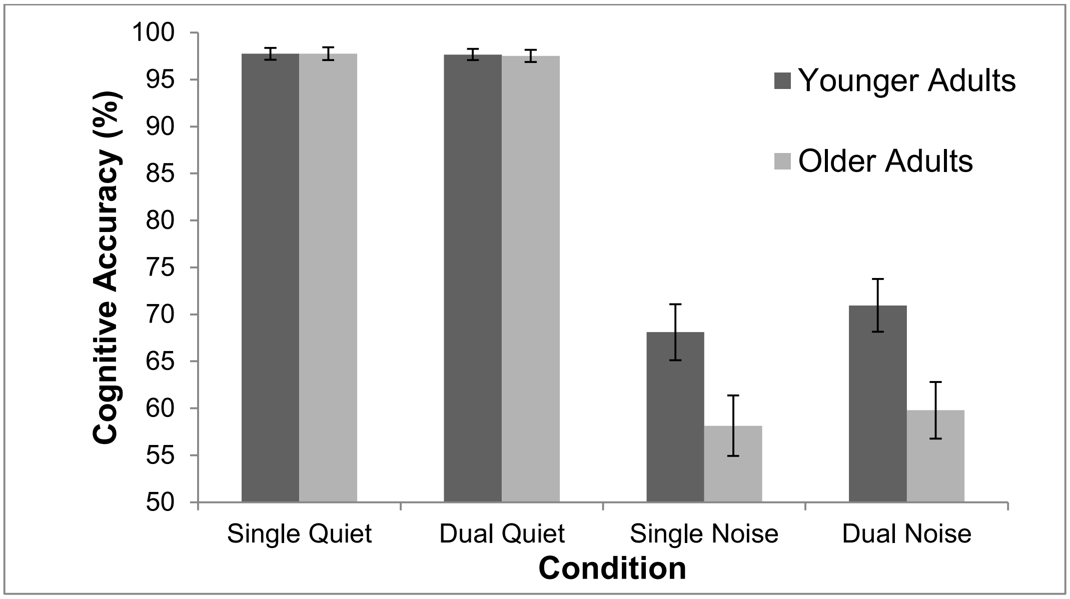
To assess cognitive performance on the 1-back working memory task, a 2 (younger adults vs. older adults) x 2 (single task vs. dual task) x 2 (quiet vs. noise) mixed factorial ANOVA was performed using the participants' accuracy scores (%) as the dependent variable (see Figure 1). The analysis revealed a significant main effect of listening difficulty, $F(1, 52) = 271.86$, $p < .001$, $\eta_p^2 = .84$, such that cognitive performance was higher in quiet ($M = 97.66$, $SD = .42$) than noisy conditions ($M = 64.25$, $SD = 2.01$). There

Table 1.
Means and standard deviations for all baseline measures

Source	*Younger Adults*	*Older Adults*	*p*
Age (years)	21.83 (3.01)	65.32 (3.26)	<.001**
Years of Education	14.15 (1.10)	16.61 (1.53)	<.001**
ABC (max 100)	94.53 (5.39)	96.75 (2.90)	.071
LSEQ (max 100)	89.83 (7.33)	84.69 (10.0)	.034*
Letter-Number Sequencing (max 30)	19.66 (2.04)	19.04 (2.86)	.363
LNS Longest Span	5.38 (0.86)	5.12 (1.01)	.314
Digit Symbol (max 84)	81.52 (8.79)	73.12 (12.94)	.007**
DKEFS Trails Condition Two (seconds)	24.13 (4.43)	33.05 (13.51)	.002**
DKEFS Trails Condition Three (seconds)	26.27 (6.05)	32.10 (10.68)	.016*
DKEFS Trails Condition Four (seconds)	63.24 (21.84)	73.14 (27.25)	.144
Average Hearing Threshold (dB)	11.72 (3.81)	18.48 (3.21)	<.001**
Sit-to-Stand (seconds)	10.07 (1.59)	12.93 (3.05)	<.001**
ETDRS Right Eye (M-unit)	23.76 (10.20)	32.38 (12.00)	.007**
ETDRS Left Eye (M-unit)	23.66 (11.04)	30.00 (11.04)	.042

Note. *$p < .05$ and **$p < .01$ for independent samples *t*-tests

Figure 1. Cognitive 1-back Task Accuracy (%) as a function of age group, auditory challenge, and attentional load.



Note. Error bars represent one standard error of the mean.

was also a significant main effect of attentional load $F(1, 52) = 5.53$, $p = .023$, $\eta_p^2 = .10$, such that participants had higher accuracy scores in dual-task ($M = 81.48$, $SD = 1.11$) than single-task ($M = 80.43$, $SD = 1.16$) conditions. Analyses also revealed a significant main effect of age group, $F(1, 52) = 5.71$, $p = .021$, $\eta_p^2 = .10$, wherein the younger adults had higher cognitive accuracy scores ($M = 83.61$, $SD = 1.51$) compared to the older adults ($M = 78.30$, $SD = 1.63$). Furthermore, significant interactions were observed for age group and auditory challenge, $F\ (1, 52) = 6.71$, $p = .012$, $\eta_p^2 = .11$, and for auditory challenge and attentional load, $F\ (1, 52) = 6.72$, $p = .012$, $\eta_p^2 = .11$. All remaining main effects and interactions were not statistically significant (ps $\geq .454$).

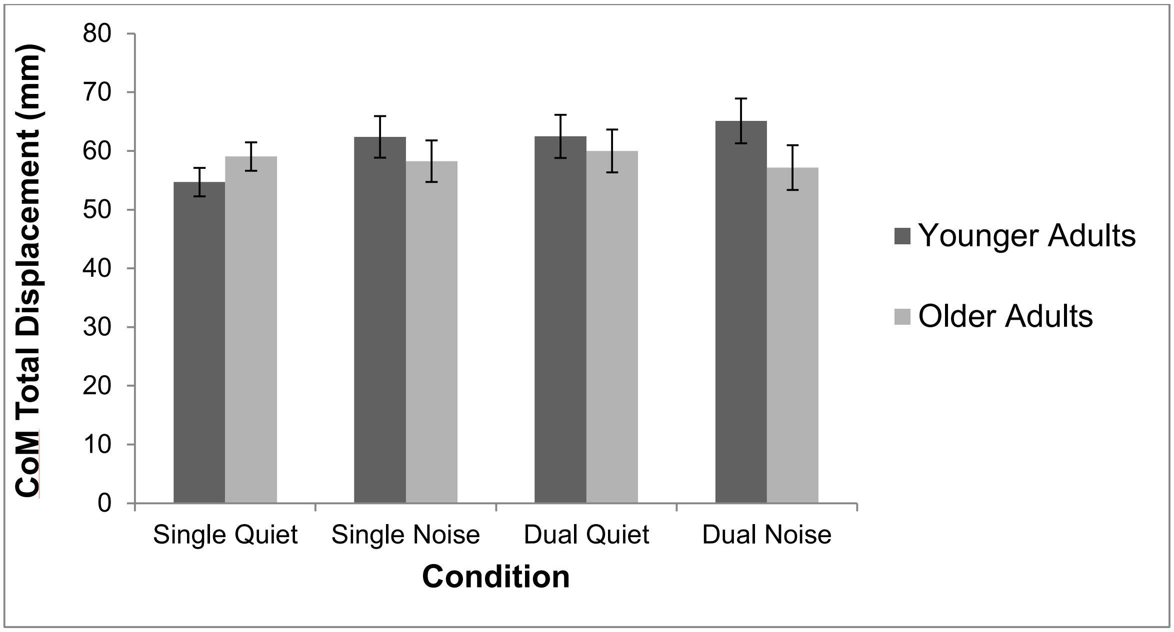
To explore the interaction between age group and auditory challenge, separate 2 (attentional load) x 2 (age group) repeated measures ANOVAs were carried out for each listening condition. Results revealed that in quiet conditions, older adults' accuracy scores ($M = 97.63$, $SD = .62$) were not statistically significantly different from those of younger adults ($M = 97.70$, $SD = .58$), $F(1, 52) = .006$, $p = .939$. However in noisy conditions, younger adults ($M = 69.53$, $SD = 2.84$) had significantly higher accuracy scores compared to older adults ($M = 58.97$, $SD = 3.06$), $F(1, 52) = 949.48$, $p < .001$. To explore the interaction between auditory challenge and attentional load, a series of paired samples t-test were conducted. Pooling across the two groups, accuracy scores were significantly higher in dual noise conditions ($M = 65.38$, $SD = 2.17$) compared to single noise conditions ($M = 63.49$, $SD = 2.28$), $t(53) = -2.73$, $p = .009$. Accuracy scores on single quiet ($M = 97.74$, $SD = .47$) and dual quiet ($M = 97.59$, $SD = .44$) conditions were not statistically significantly different, $t(53) = .45$, $p = .656$.

Balance Analysis

A subset of thirteen younger (*M* = 22.54, *SD* = 2.50) and thirteen older (*M* = 65.31, *SD* = 4.05) adults were analyzed for balance performance due to time constraints. The subset was chosen based on participants without significant amounts of missing data. Independent samples *t*-tests were conducted to confirm that each subset (balance data analyzed) did not differ from the rest of their respective age group (balance data not analyzed) on any of the background measures and therefore are considered to be representative of the larger samples tested (*p*s ≥ .068).

Total CoM Distance (mm). The total CoM distance (sum of peak backward and forward displacements) provides a global measure of postural sway following the platform movement. A 2 (younger adults vs. older adults) x 2 (single task vs. dual task) x 2 (quiet vs. noise) mixed factorial ANOVA was performed using total CoM distance as the dependent variable (see Figure 2). Analyses revealed an interaction of age group and auditory challenge, $F(1, 24) = 7.19$, $p = .013$, $\eta_p^2 = .23$, and an interaction of age group and attentional load, $F(1, 24) = 4.89$, $p = .037$, $\eta_p^2 = .17$. All remaining main effects and interactions were not statistically significant (*p*s ≥ .204). Post-hoc analyses were then performed to explore the interaction using separate 2 (single task vs. dual task) x 2 (quiet vs. noise) repeated measures ANOVAs for each age group. While older adults were invariant across conditions (*p*s ≥ .365), there was a main effect of listening condition among younger adults $F(1,12) = 8.52$, $p = .013$, $\eta_p^2 = .42$ such that they demonstrated greater CoM distance in noisy (*M* = 63.77, *SD* = 4.52) compared to quiet (*M* = 58.60, *SD* = 3.50) conditions. Similarly, while older adults were invariant across single- and dual-task conditions (*p*s ≥ .365), younger adults demonstrated greater CoM distance in dual-task (*M*

Figure 2. Total CoM Distance (mm) by condition.



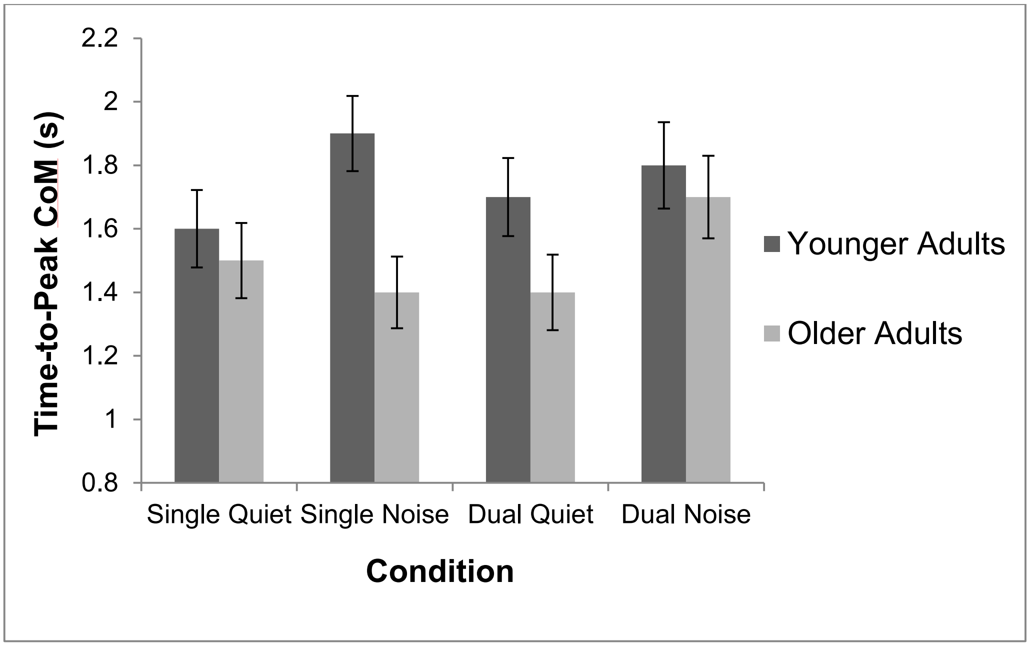
Note. Error bars represent one standard error of the mean.

= 63.81, *SD* = 4.58) compared to single-task conditions (*M* = 58.54, *SD* = 3.47), $F(1,12) = 7.30$, $p = .019$, $\eta_p^2 = .38$.

CoM Time-To-Peak (s). CoM Time-to-Peak is the time that elapsed between the perturbation onset and when the individual reached their minimum CoM displacement (i.e., farthest forward movement). A longer time-to-peak can be indicative of greater control in the recovery phase and possible dampening of the movement following a perturbation. A 2 (younger adults vs. older adults) x 2 (single task vs. dual task) x 2 (quiet vs. noise) mixed factorial ANOVA was performed with the CoM time-to-peak as the dependent variable (see Figure 3). Analyses revealed a main effect of age group, $F(1, 23) = 5.81$, $p = .024$, $\eta_p^2 = .20$, such that younger adults exhibited a longer CoM time to peak (*M* = 1.75, *SD* = .09) when compared to older adults (*M* = 1.44, *SD* = .09). There was also a significant 3-way interaction of age group, attentional load and listening difficulty, $F(1, 23) = 6.69$, $p = .016$, $\eta_p^2 = .23$. All remaining main effects and interactions were not statistically significant (ps ≥ .209). To explore the significant 3-way interaction, a series of independent samples *t*-tests were conducted for each of the four conditions. Younger adults demonstrated a longer CoM time-to-peak in single noise conditions (*M* = 1.91, *SD* = .12) compared to their older counterparts (*M* = 1.39, *SD* = .11), $t(23) = 3.17$, $p = .004$. None of the other comparisons were statistically significant (ps ≥ .064).

CoM Time-To-Maximum Displacement (s). CoM Time-to-Maximum Displacement is the time that elapsed between the perturbation onset and when the individual reached their maximum CoM displacement (backwards movement). Similar to CoM time-to-peak, this parameter can be indicative of controlled movement (longer time)

Figure 3. CoM Time-to-Peak (s) by condition.



Note. Error bars represent one standard error of the mean.

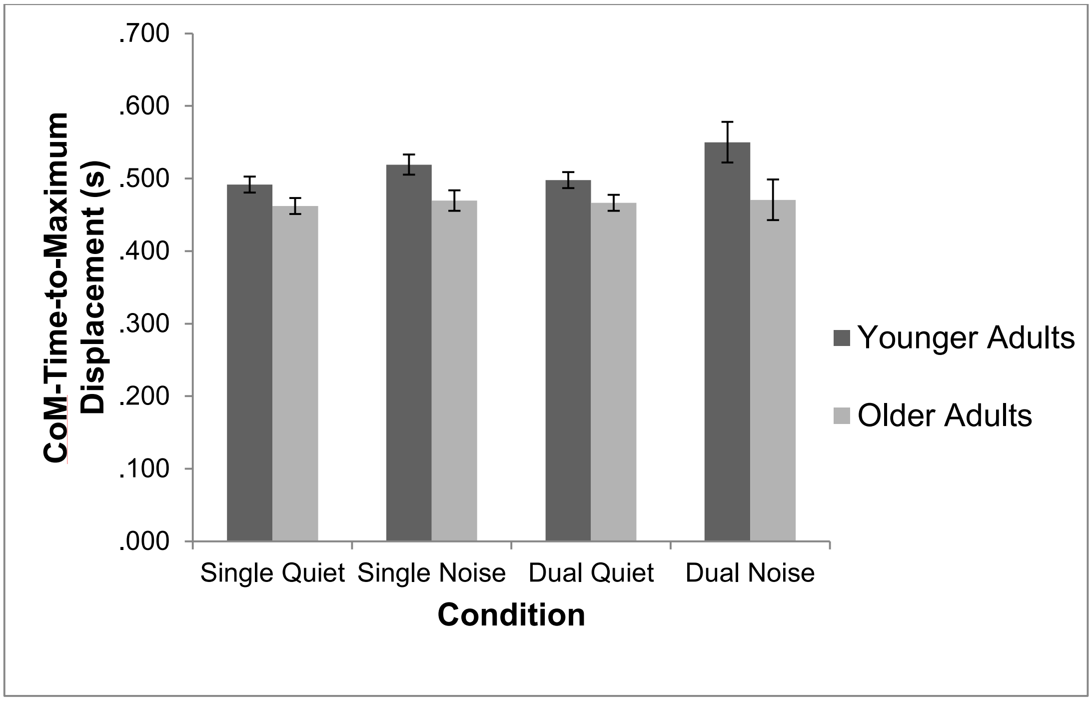
as opposed to jerky or ballistic movement (shorter time). A 2 (younger adults vs. older adults) x 2 (single task vs. dual task) x 2 (quiet vs. noise) mixed factorial ANOVA was performed with the CoM time-to-maximum displacement as the dependent variable (see Figure 4). Analyses revealed a main effect of age group, $F(1, 24) = 5.97$, $p = .022$, $\eta_p^2 = .199$, such that younger adults exhibited a longer CoM time to maximum displacement ($M = .52$, $SD = .01$) when compared to older adults ($M = .47$, $SD = .01$). None of the other main effects or interactions were statistically significant (ps $\geq .092$).

Correlations

All correlations were calculated separately for each age group. Intercorrelations between performance on the cognitive task and balance parameters in dual-task conditions were calculated to explore the possibility of a trade-off between cognitive and balance task performance. No correlations were found to be statistically significant (ps $\geq .127$).

Intercorrelations were also calculated between cognitive task performance and background measures to investigate what factors might have influenced participants' strategies when completing the cognitive task (see Table 2). Different patterns were found for each age group. For younger adults statistically significant correlations were found between performance on the cognitive task and the letter-number sequencing task in all conditions and performance on the cognitive task and digit symbol task in noisy conditions indicating that higher performance on the background measures was associated with greater performance on the cognitive task. Among older adults, the correlation between performance on the cognitive task and digit symbol task was found to be statistically significant in quiet conditions such that higher scores on this measure of processing speed was associated with an increased performance on the cognitive task.

Figure 4. CoM Time-to-Maximum Displacement (s) by condition.



Note. Error bars represent one standard error of the mean.

Table 2.
Correlations between Background Variables and Cognitive Accuracy per Condition

	Digit Symbol	LNS	D-KEFS 2	D-KEFS 3	D-KEFS 4	Single Quiet	Single Noise	Dual Quiet	Dual Noise
Digit Symbol	1	.293	-.497**	-.207	-.395*	.127	.429*	.079	.403*
LNS	.612**	1	-.114	-.352	-.261	.407*	.392*	.409*	.445*
D-KEFS 2	-.473*	-.281	1	.440*	.472**	.060	-.260	-.189	-.214
D-KEFS 3	-.478*	-.368	.854**	1	.372*	-.375*	-.330	-.426*	-.480**
D-KEFS 4	-.593**	-.491*	.755**	.882**	1	.068	-.089	-.209	-.220
Single Quiet	.458*	.378	-.329	-.302	-.439*	1	.495**	.479**	.552**
Single Noise	-.016	.089	.061	-.106	.057	.019	1	.582**	.938**
Dual Quiet	.426*	.319	-.244	-.263	-.345	.819**	.140	1	.604**
Dual Noise	-.130	-.039	.188	.008	.168	-.030	.912**	.085	1

Note. Values above the diagonal represent younger adults and values below the diagonal represent older adults. LNS: Letter-number sequencing.

Note. *p < .05 and **p < .01 for correlations.

Discussion

The purpose of the current study was to experimentally integrate the two domains of auditory and motor functioning to better understand their correlation using a dual-task method to challenge older adults in both hearing (i.e., auditory cognitive task) and motor (i.e., balance) domains. Of interest was the impact of auditory challenge (noise) on cognitive and balance performance, and whether postural recovery would be influenced by the addition of a concurrent auditory cognitive task. It was hypothesized that older adults would show greater dual-task costs when compared with their younger counterparts and that performance costs would be exacerbated by attentional load (i.e., dual-task) and auditory challenge (i.e., noise). Furthermore, in line with the posture first principle, we anticipated that older adults would prioritize balance performance over cognitive performance due to the ecological value of balancing, whereas young adults would be able to more flexibly distribute their attentional resources between the auditory task and the balance task.

Cognitive performance was first evaluated in order to investigate the potential impact of age, attentional load (i.e., dual-task) and auditory challenge (i.e., noise), with the premise that with age, cognitive resources become more limited and therefore performance might be more negatively impacted by an increased attentional load or when information has to be extracted from a noisy environment. As predicted, older adults generally demonstrated lower performance on a task of working memory when compared with younger adults. Furthermore, all participants were negatively impacted by the addition of noise and most importantly for our hypothesis and congruent with prior research on the effect of babble (Pichora-Fuller et al., 1995), this noise effect was magnified among older adults. This finding is particular notable given that the intensity and SNR of the auditory stimuli were calibrated for each individual participant according to their absolute hearing threshold. Interestingly, across all participants, the addition of noise was facilitative to dual-task cognitive performance when compared with the single-task condition. In contrast to our hypothesis and other work in the area (Brauer, Woollacott, & Shumway-Cook, 2002; Brown et al., 1999), there was no cognitive dual-task cost meaning that the attentional load manipulation did not significantly impede cognitive performance in either age group. Of further note, the correlational analyses of auditory *n*-back and neuropsychological test scores revealed a different pattern of associations for young adults (working memory LNS) compared to older adults (processing speed digit symbol coding). These results suggest that older and younger adults may have used qualitatively different strategies to perform the auditory *n*-back task.

Turning to the parameters reflecting postural recovery, it was also of interest to study the impact of aging, dual-tasking and auditory challenge on the magnitude of displacement and latency of backward and forward movements, given their hypothesized reliance on cognitive capacity. Based on previous work (Maki, Zecevic, Bateni, Kirshenbaum, & McIlroy, 2001; Norrie et al., 2002; Quant et al., 2004), one would expect attentional load effects to be more pronounced during later phases of the postural response (forward movement), which are less reflexive and therefore may utilize more cognitive resources. Consistent with our hypothesis and previous work, age group differences in postural recovery were found in the later portion of the reaction (i.e., Total CoM Distance, CoM Time-to-Peak) with patterns suggesting a prioritization of posture with aging. More specifically, while older adults' balance remained invariant across conditions, younger adults demonstrated greater total CoM distance in noisy and dual-task conditions compared to quiet and single-task conditions. Furthermore, while older adults demonstrated a conservative response, younger adults took longer to reach their minimum CoM distance overall particularly in single noisy conditions. Differences in postural response were also found in the early reflexive reaction to the platform perturbation where younger adults took longer to reach their maximum CoM displacement than older adults. This finding adds to recently published work demonstrating a dual-task cognitive effect with increasing postural demand in this early more automatic response (Little & Woollacott, 2014).

Findings from the current study converge with other research (Doumas, Smolders, & Krampe, 2008; Lajoie et al., 1993; Li et al., 2001; Redfern, Muller, Jennings, & Furman, 2002) by revealing that older adults displayed a more conservative and rigid response to a challenging threat to balance, remaining invariant across conditions while younger adults allowed for more instability and movement thereby demonstrating flexibility in how they allocated their attention. For example, in the least threatening balance conditions, older adults allow for more instability (i.e., increased sway) in order to release resources necessary to accommodate performance on a secondary task. However, when postural conditions become more challenging, older adults maintain the same postural response across both single and dual-task conditions, suggesting a reluctance to divert attention away from balancing (Doumas et al., 2008). This similar pattern of finding in the current study suggests that younger adults were able to respond to task manipulations (i.e., addition of noise or concurrent task) and flexibly split attention between the two tasks, while older adults maintained a posture first response as a means of protecting balance

(Doumas et al., 2008; Fraser, Li, DeMont, & Penhune, 2007; Kemper et al., 2002; Schaefer & Schumacher, 2011; Lajoie et al., 1993; Li et al., 2001; Redfern et al., 2002). These results fit into a larger picture of research demonstrating that older adults adapt their resource allocation according to task prioritization as a means of compensation for age-related declines in sensorimotor and cognitive processing (Doumas et al., 2008; Li et al., 2005).

In the extant research, a second pattern of support for postural prioritization comes from dual-task studies in which cognitive dual-task costs are greater for older adults than young adults, but motor dual-task costs are age-invariant (e.g., Li et al., 2001). More specifically, if older adults are protecting posture and showing compensation, we would expect them to allocate more attention to posture than to cognition. While the current findings support the first pattern indicating postural prioritization, they do not align with the second pattern. To some extent, this discrepancy could be a function of the overall challenge of the tasks. More specifically, it is possible that our working memory task and/or platform perturbation was not challenging enough to elicit dual-task costs as all participants performed at ceiling on the cognitive task in quiet conditions. Therefore if cognitive resources were not being sufficiently taxed, and there was residual capacity, declines in cognitive performance may not manifest. To experimentally investigate this possibility it would be necessary to increase the level of challenge of the working memory task (i.e., 2-back working memory) and/or the perturbation as has been done in other studies where dual-task cognitive costs were found (i.e., Brown et al., 1999; Doumas et al., 2007).

Another possible explanation for the lack of cognitive dual-task costs is that compensation occurred at a neural level where previous studies have demonstrated that even under the simplest single-task condition, older adults engage in compensatory brain activation, a pattern which is magnified in dual-task conditions (Erikson et al., 2005). Therefore, although there were no cognitive performance costs from single to dual-task conditions in the present study, it is possible that participants were exhibiting increased brain activation, thus compensating for an increase in task difficulty at a neural level. Lastly, it is possible that age differences in cognitive dual-task costs were not seen due to the manner in which the cognitive data were analyzed. Whereas the postural response was decomposed into these two distinct phases (backward maximum excursion; forward minimum excursion) in the balance data, the cognitive data were considered as a whole. When considering recovery from a perturbation, there are broadly two different stages – an early reflexive part and a later more controlled stage (Maki & McIlroy, 2007). Dual-task costs are generally more pronounced in the controlled stage, therefore isolating cognitive responses that coincided with this later phase should provide a more sensitive index of cognitive dual-task costs and potentially reveal age differences as predicted. In future, a similar decomposition of the cognitive data into early and late phases relative to platform perturbation onsets might be fruitful. Alternatively in future work one could measure verbal response latencies for the cognitive task and analyze them in relation to the perturbation onsets.

Considering the cognitive and balance results together, the manipulation of listening challenge (noise) had a greater negative impact on task performance than the dual-task manipulation. The noise manipulation differentially hindered older adults' performance despite the care taken to individually calibrate auditory stimulus intensities and hold SNR constant across individuals. These results are in line with the Cognitive Compensation view in that adding an auditory challenge should lead to cognitive compensation and limit overall cognitive capacity (Li & Lindenberger, 2002).

Interestingly, in noisy conditions cognitive performance was facilitated by dual-tasking. Although seemingly counterintuitive at first, previous work in posture (Huxhold, et al., 2006) suggests that lower level cognitive tasks can be facilitative of postural performance. Furthermore, Yerkes and Dodson (1908) observed a negative quadratic relation between arousal and performance wherein performance increases with physiological and mental arousal to a point, after which performance declines. Therefore, it is possible that the mild perturbation was facilitative of cognitive performance because it created an optimal level of arousal.

The results of the present study should be interpreted as preliminary, due to several limitations. Firstly, the sample subset analyzed for balance performance was small and therefore may not have been adequately powered to detect differences between groups. Furthermore, the sample of younger adults was based solely on Concordia University students and calls into to question the extent to which the conclusions can be generalized to the population at large. Future directions for the project include recruiting a third group of older adults with mild hearing loss in order to study their pattern of compensation. Based on preliminary data from this third group, it is expected that older adults with mild hearing loss will demonstrate substantially greater performance costs and noise effects than healthy older adults with normal hearing.

The current work complements the established epidemiological evidence linking hearing loss and reduced mobility (Viljanen et al., 2009) and is novel in providing experimental evidence that implicates cognitive capacity as an underlying factor. The results align with the theoretical approaches concerning cognitive compensation and postural prioritization in older adults. Evidence of the interdependence of sensory, motor and cognitive factors in old age could be used to inform and train those working in the field of geriatrics and audiology regarding best practice. For example, rehabilitation programs to benefit older adults with hearing loss targeting the sensory loss with hearing aids could potentially be enhanced by adding cognitive remediation training. Furthermore, findings could be used to inform mobility training programs for older adults wherein training cognitive control processes might not only enhance cognitive abilities, but could also be used to improve sensorimotor abilities in older adults (Li et al., 2010). Previous training interventions (i.e., muscle strengthening, walking, tai chi) for mobility have focused largely on the physical aspects of motor functioning to generate significant improvements in postural control, chair rising, and falls incidence (Melzer, Benjuya, & Kaplanski, 2003; Orr et al., 2006; Wolf et al., 2006). However, training older adults on more ecologically relevant dual-tasks in both cognitive and mobility domains may translate to real-life improvements such as improved walking while talking and reduce the elevated risk for falls in older adults with hearing loss.

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Appendix A

Demographic questionnaire.

We are interested in your personal history because it may help us to better understand the results of our study. Your answers to a few short questions will aid us in this effort. All answers will be kept strictly confidential. Thank you for your help.

Demographics:

1. Date of Birth (D/M/Y): _______________

2. Age: _______________

3. Gender: (*circle response)* (1) MALE (2) FEMALE

4. Handedness: (*circle response)* (1) LEFT (2) RIGHT (3) BOTH

5. Present marital status: *(circle response)* (1) Single – never married (2) Married

   (3) Separated (4) Divorced (5) Widowed

Ethnicity:

Please indicate your ethnic origin by choosing one of the ten categories listed below. Ethnic origin refers to the ethnic or cultural group(s) to which your recent ancestors belonged. If you have multiple ethnic origins, then please select the one with which you most strongly identify; if this is not possible, then please choose option 10.

1 – European (including British Isles)
2 – East and Southeast Asian (e.g., China, Japan, Korea, Vietnam)
3 – South Asian (e.g., India, Pakistan, Bangladesh, Sri Lanka)
4 – Middle Eastern
5 – African
6 – Latin, Central, and South American
7 – Caribbean
8 – Pacific Islands
9 – Aboriginal
10 – Other

Languages:

6. Place of Birth: _______________________

7. Languages Spoken (in order of fluency): ________________________

8. Primary Language Spoken/Language of Choice: ________________________

9. Language at Home:___________________________

10. Language At Work: ___________________________

11. Language of Education: _________________________

12. At what age did you first learn English? _________________________

13. At what age did you become fluent in it? _________________________

14. How many years of formal education do you have at this time? (i.e., what is the highest level achieved?)

1 2 3 4 5 6	7 8 9 10 11 12	13 14 15 16	17 18 19 20	21 22 23 24 25
Elementary	Secondary	Undergrad	Graduate	Professional

15. What is or was your main occupation? ___________________________

16. Have you ever been unconscious, had a head injury or had blackouts?

A) NO/YES
B) Cause: ____
C) Duration: ____
D) Treatment: ____
E) Outcome: ____

17. Have you ever been seriously ill or hospitalized in the past 6 months?
A) NO/YES
B) Cause: ____
C) Duration: ____

Do you have now, or have you had in the past?

18. a) A Stroke?	NO/YES	When?
b) Transient Ischemic Attack?	NO/YES	
19. Heart Disease?	NO/YES	Nature? (MI, Angina, narrowing of the arteries)
20. High blood pressure?	NO/YES	Is it controlled?
21. High Cholesterol?	NO/YES	

22. Bypass Surgery?	NO/YES	
23. Other Surgery?	NO/YES	
24. Seizures?	NO/YES	Age Onset:_____ Frequency:______ Cause:________ Treatment: ______
25. Epilepsy?	NO/YES	
26. a) Diabetes?	NO/YES	Type I/Type II Age of Onset:_______
b) Insulin Dependent?	NO/YES	Treatment: _____________
27. Thyroid Disease?	NO/YES	
28. Frequent Headaches?	NO/YES	Tension/migraine
29. Dizziness	NO/YES	
30. Trouble Walking? Unsteadiness?	NO/YES	
31. Arthritis?	NO/YES	
32. Any injuries to the lower limb? (e.g., hip, knee, ankle)	NO/YES	
33. Serious illness? (e.g., liver disease)	NO/YES	
34. Neurological Disorders?	NO/YES	
35. Exposure to toxic chemicals (that you know of)?	NO/YES	
36. Depression?	NO/YES	
37. Anxiety?	NO/YES	
38. Other psychological difficulties?	NO/YES	
39. Hormone replacement?	NO/YES	
40. Steroids?	NO/YES	

Medication: Please list the medication that you are currently taking and any other medication that you have taken in the past year.

Type of Medication	Reason for Consumption	Duration of Consumption or Dose

41. **Approximately how many drinks of alcohol do you have per week?**
(1 drink = 1 beer, 1 glass of wine, 1 oz of liquor) _________________________

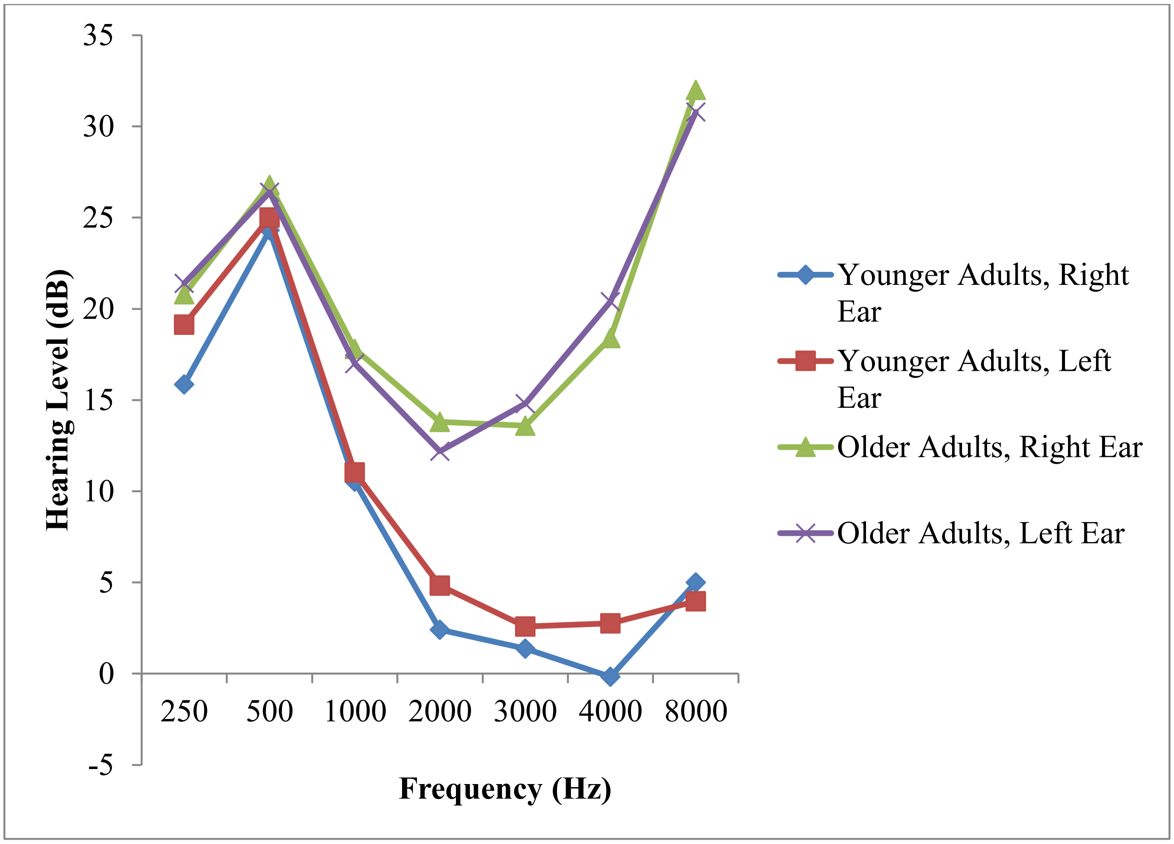
42. **Do you smoke?** NO/YES IF YES, how many packs a day?

43. **Present problems** – are you currently troubled by any of the following?

Concentration/ Attention problems	NO/YES	Nature:
Memory problems	NO/YES	Nature:
Difficulties finding words	NO/YES	Nature:

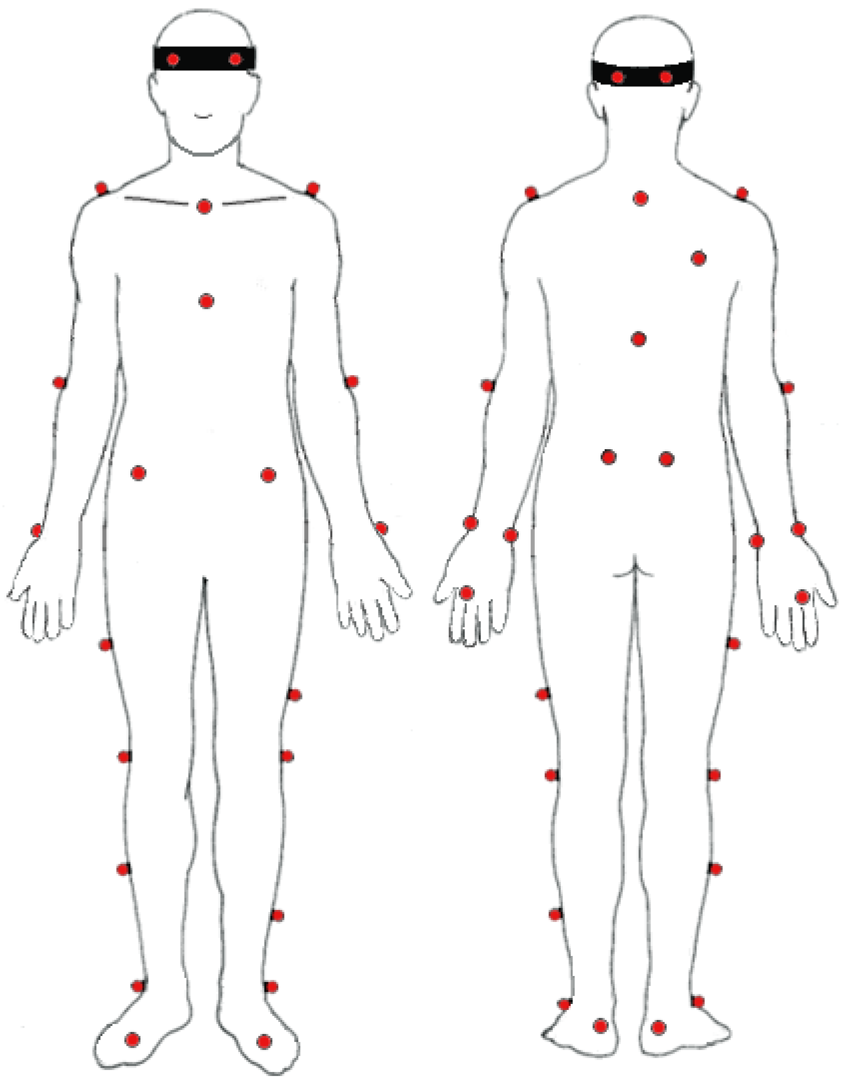
Appendix B

Average audiometric thresholds for all participants as a function of age and frequency.



Appendix C

VICON motion capture 35 whole body marker placement.



Appendix D

Procedure and Muscles for EMG.

Procedure:

1. Relevant muscles were located on the participants (see list below).
2. Area was shaved if necessary and cleaned with rubbing alcohol.
3. Sensors were placed on the belly of each muscle and then attached to electrodes.
4. All muscles were tested via voluntary contraction prior to data collection to ensure proper placement.

Muscles:

- Rectus abdominis
- Rectus femoris
- Vastus medialis
- Tibialis anterior
- Biceps femoris
- Semitendinosus
- Gastrocnemius
- Erectus spinae

Appendix E

Sample of counterbalancing; Balance, Quiet Conditions First.

Task	Auditory Condition	Number of Trials
Cognitive Practice		3
Balance		1
Cognitive	Quiet	5
Balance	Quiet	5
	BREAK	
Dual-task (cognitive and balance tasks)	Quiet	5
	BREAK	
Dual-task (cognitive and balance tasks)	Quiet	5
	BREAK	
Balance	Quiet	5
Cognitive	Quiet	5
	BREAK	
Cognitive	Noise	5
Balance	Noise	5
	BREAK	
Dual-task (cognitive and balance tasks)	Noise	5
	BREAK	
Dual-task (cognitive and balance tasks)	Noise	5
	BREAK	
Balance	Noise	5
Cognitive	Noise	5

Appendix F

Graphical representation of balance dependent variables of interest.