Age-related hearing loss and gait adaptations: Postural prioritization during concurrent walking and listening tasks

Victoria Nieborowska

A Thesis

In

The Department

Of

Psychology

Presented in Partial Fulfillment of the Requirements for the Degree of Master of Arts
(Psychology) at Concordia University
Montréal, Québec, Canada.

September 2015

Concordia University

School of Graduate Studies

This is to certify that the thesis prepared

By: Victoria Nieborowska

Entitled: Age-related hearing loss and gait adaptations: Postural prioritization during concurrent walking and listening tasks

and submitted in partial fulfillment of the requirements for the degree of

Master of Arts (Psychology)

complies with the regulations of the University and meets the accepted standards with respect to originality and quality.

Signed by the final examining committee:

Dr. Andrew Chapman	Chair
Dr. Aaron Johnson	Examiner
Dr. Nancy St-Onge	Examiner
Dr. Karen Li	Supervisor

Approved by: ______________________________
Chair of Department or Graduate Program Director

____
Dean of Faculty

____
Date

Table of Contents

Abstract

Age-normative hearing loss is linked with reduced cognitive functioning, mobility decline, and increased falls risk in older adults. One explanation, as yet untested experimentally, is that with age, there are increasing demands for limited cognitive capacity required to successfully perform walking and listening. To address this gap, the current study investigated age-related differences in the allocation of cognitive resources between concurrent walking and listening tasks. Seventeen younger and twelve older adults with normal hearing participated. Three sentences (1 target, 2 maskers) were played simultaneously from apparent auditory scene locations (left, center, right) in a virtual reality street crossing scene. Target location probability (100% versus ≤75%) was varied. Participants reported key elements from the target sentences. Gait during self-paced treadmill walking was assessed with a motion capture system using active markers positioned on the head, sternum, waist, and feet. Participants completed five conditions: walking only, listening only 100% probability, listening only ≤75% probability, walking while listening 100% probability, and walking while listening ≤75%. Key dependent measures were listening accuracy, head and trunk position, and gait parameters (e.g., step width, stride length, stride time, stride time variability, velocity, and cadence). Word recognition accuracy was significantly worse in (a) older than younger adults, (b) dual- than single-task, and (c) less predictable location probability. Kinematic analyses revealed reduced average head pitch and stride time variability, but increased variability in cadence from single-task walking to dual-task conditions in older adults. Younger adults did not exhibit a consistent gait pattern. Overall, older adults displayed more dual-task costs in listening performance, but younger adults showed more performance costs in motor function. A closer examination of performance costs revealed that older adults who demonstrated improved posture through reduced head pitch rotation were also better at listening under dual-task conditions. Altogether, listening in a multitalker situation in old age was particularly hampered when concurrently walking and when the signal location was less predictable. Furthermore, under increased cognitive load, older adults displayed reduced gait variability in stride time, and straightened their head alignment. These findings suggest that older adults redistribute cognitive resources toward gait over listening performance, consistent with theories of postural prioritization and cognitive compensation.

Age-related hearing loss and gait adaptations: Postural prioritization during concurrent walking and listening tasks

The prevalence of hearing loss in older adults aged over 65 is approximately 1 in 3 people, and expected to increase as the baby boom population ages (Lin, Thorpe, Gordon-Salant, & Ferrucci, 2011). This demographic trend underscores the importance of research on successful aging that allows older adults to manage everyday activities needed for an independent life. Normal aging is accompanied with decline in sensory, motor, and cognitive modalities, which can adversely affect functional status and quality of life. A link between sensory and cognitive functions has been suggested given that they share similar developmental trajectories (Anstey, Hofer, & Luszcz, 2003). Indeed, cross-sectional and longitudinal evidence shows a strong age-related increase in the association between sensory, sensorimotor, and fluid intellectual abilities in late life (Anstey et al., 2003; Baltes & Lindenberger, 1997; Lin et al., 2011; Lindenberger & Baltes, 1994; Lindenberger & Ghisletta, 2009; Lövdén, Ghisletta, & Lindenberger, 2004; Valentijn et al., 2005). Measures of hearing and visual acuity, as well as balance/gait were found to share increasing variance with intellectual abilities in old age (Baltes & Lindenberger, 1997; Salthouse, 1991). In addition, hearing loss in older adults is associated with slower gait speed, mobility decline, and balance impairments that ultimately lead to greater falls risk (Gerson, Jarjoura, & McCord, 1989; Li, Simonsick, Ferrucci, & Lin, 2013; Viljanen et al., 2009a). It is proposed that the connection between hearing loss, balance disruptions, and falls are interdependent (Viljanen et al., 2009b). Researchers have shown that older adults with poor hearing have a twofold risk for falls compared to peers with normal hearing (Viljanen et al., 2009b). However, the exact nature of this connection is largely uncertain. Specifically, there is paucity of experimental research on the relation between hearing acuity and falls risk in the elderly (Viljanen et al., 2009b).

The aim of the present study is to investigate the underlying mechanism between age-normative hearing loss and mobility function, which in turn affects falls risk. The literature reviewed here summarizes the current knowledge on auditory and mobility decline in late life. In particular, the focus of this review will be on the interplay between cognitive and perceptual processes implicated in hearing and mobility. Subsequently, several alternative hypotheses regarding the link between these domains will be described.

Age-Dependent Hearing Loss and Speech Understanding

With advancing age, peripheral, and cognitive operations decline, which together contribute to difficulty in understanding speech. Anatomical and physiological transformations of the auditory system negatively affect the ability to process sound, and clinically significant changes in threshold sensitivity can lead to presbycusis (Schneider & Pichora-Fuller, 2000). Presbycusis or age-related hearing loss (a decrease in hearing sensitivity of primarily high frequency sounds) is one of the most common health and social problems in the elderly (Walling & Dickson, 2012). In Canada, presbycusis affects 6.4% of older adults aged 55 – 64; 12% aged 65 – 74%; and 26% aged 75 and older (Statistics Canada, 2006). Although the etiology of presbycusis is not well defined, it is shown that hereditary susceptibility, cardiovascular health (influenced by diabetes mellitus and tobacco smoking), along with environment, including noise exposure, alcohol abuse, chemicals, and head trauma, contribute to age-related hearing loss (for a review, see Fransen, Lemkens, van Laer, & van Camp, 2003; Parham, Lin, Coelho, Sataloff, & Gates, 2013; Schuknecht, 1964). Decreased hearing sensitivity is commonly a result of sensorineural processes, in which the atrophy of hair cells in the high-tone frequency area of the basiliar membrane causes reduced acuity for high-frequencies sounds (Wingfield, Tun, & McCoy, 2005).

Older adults, even with clinically normal hearing, commonly report difficulty in understanding speech, particularly in noisy, multitalker and/or reverberant situations (CHABA, 1988; Pichora-Fuller, Schneider, & Daneman, 1995; Tun & Wingfield, 1999; Helfer, 1992). Older adults often experience anxiety and frustration tied to these complaints, which might lead to cessation of social activity, and subsequent social isolation. In order to successfully understand speech, the listener must perceive and identify speech sounds and words uttered by the speaker. The listener must then integrate the spoken words and sentences into a meaningful message. Subsequently, the listener must attend to the speaker in order for the message to be correctly interpreted, taking into account the social and physical situation. This message is then maintained in working memory along with information being stored into long-term memory while speech is on-going (Pichora-Fuller, 2003a).

Differences between young and elderly listeners in understanding speech may be attributed to age-related differences in peripheral factors, cognitive operations, or the central auditory nervous system (CHABA, 1988). First, age-related difficulties in peripheral processing (e.g., increases in auditory threshold and auditory filters, temporal synchrony declines) might disrupt the auditory signal for cognitive and linguistic processing (Li, Daneman, Qi, & Schneider, 2004; Schneider & Pichora-Fuller, 2000). In addition, comprehension difficulties might be due to considerable decline in executive functions involving working memory (Balota, Dolan, & Duchek, 2000; Zacks, Hasher, & Li, 2000), task switching (Kramer, Hahn, & Gopher, 1999), processing speed (Salthouse, 1996), attention (Madden, 1990), and inhibition (Hasher & Zacks, 1988). Degradation of cognitive processing negatively affects one’s ability to comprehend written language and speech understanding (CHABA, 1988). For example, cognitive slowing might explain the difficulty older adults experience as they follow a conversation where speech is rapid and consists of multiple speakers (Li et al., 2004). Tun, O'Kane, and Wingfield (2002) proposed that older adults complain about hearing in noisy backgrounds due to auditory decline and trouble inhibiting irrelevant speech. Another source consists of disruptions in central auditory processing, which may result in diminished efficiency of temporal resolution that involves the ability to detect and hold the order of rapidly arriving sounds, as well as spectral resolution, wherein frequency components of sound signals are segregated (Wingfield et al., 2005). All these factors are valid explanations for difficulties reported by the elderly, wherein some may suffer purely peripheral, central-auditory, or cognitive disruptions (Humes, 1996). Furthermore, there is also considerable overlap and interaction between these three forms of information processing (Wingfield et al., 2005). In addition, it is shown that perceptual and cognitive degeneration are highly correlated (Baltes & Lindenberger, 1997; Lindenberger & Baltes, 1994).

Can the independent contributions of sensory and cognitive factors involved in speech understanding among older adults be investigated? The difficulty in examining this question stems from the fact that individuals with sensory impairments, as seen in elderly adults, are disadvantaged when administered intellectual tests that may pose sensory challenges as well as measuring cognitive ability (Lindenberger, Scherer, & Baltes, 2001). One solution is an age-simulation approach to control sensory levels between younger and older adults. Many studies have investigated tasks of working memory, since speech understanding heavily relies on maintaining information during on-going speech and the ability to manipulate stored material (Pichora-Fuller et al., 1995). Thus, it is expected that deficits in working memory used to understand speech would be greater in older adults, particularly when speech is embedded in noise. In early work, Rabbitt (1968) found that young and old participants were less likely to correctly recall a list of digits and passages when presented in noise than in quiet. One potential explanation is that the noise did not influence the intelligibility of speech, rather it increased the amount of listening effort required to discriminate the speech from noise that calls upon attentional resources to rehearse target words. In order to test whether sensory decline contributes to cognitive performance, Lindenberger, Scherer, and Baltes (2001) administered a battery of cognitive tasks to middle-aged adults under reduced visual acuity using partial occlusion filters, or reduced hearing acuity through headphone noise protectors, while other participants were given a placebo reduction of visual acuity or auditory acuity or no treatment. The only detrimental effect found was when auditory acuity was reduced on measures of working memory compared to other groups with manipulated sensory reductions and controls. Similarly, Rabbitt (1991) found that older participants with hearing loss had reduced accuracy on a free recall task than older adults with normal hearing. The author concluded that the degradation of the auditory signal through noise is equivalent to difficulty imposed by hearing loss that has a negative effect on recall accuracy, even if the words had been identified.

Altogether, these studies suggest that when age-simulated decreases in sensory acuity were imposed, middle-aged and older adults invested more effort to compensate for more challenging conditions (Rabbit, 1968). Unlike quiet listening conditions that rely on bottom-up perceptual processes and do not tax working memory, unfavourable signal-to-noise ratios (SNR) exhaust top-down resources that would ordinarily be used for working memory (Pichora-Fuller et al., 1995). Noise can be presented in different ways, such as white noise or pink noise (i.e., forms of speech-shaped noise that range across all frequencies with different power spectral density) and babble (i.e., multiple speakers talking simultaneously). Pichora-Fuller and colleagues (1995) reported that only when the SNR of young adults were equated to older adults did performance in working memory become comparable across age groups. It is shown that the intelligibility of simple words can change up to 20% with a 1-dB SNR change (Duquesnoy, 1983). Generally, as the SNR becomes unfavourable, more effortful listening is utilized which diverts cognitive resources from higher level cognitive and linguistic processing (Pichora-Fuller et al., 1995), or effective encoding of information into long term memory (Murphy et al. (2000). Thus, speech understanding difficulties may largely reflect perceptual impairments rather than cognitive decline in the elderly (Murphy, Daneman, & Schneider, 2006).

Another experimental approach used to understand the interplay between cognitive and sensory processes in the elderly is to add a simultaneous cognitive load to the primary task, which is often termed the dual-task paradigm. This method experimentally simulates age-related declines in cognitive function through the presentation of simultaneous or concurrent tasks. The concept of occupying cognitive resources with a secondary task dates back to Kahneman's influential resource theory (1973), in which he proposed that there is limited cognitive capacity, and the ability to respond to two tasks simultaneously depends on the demands of those activities wherein attention must be divided. Cognitive resources are allocated toward a primary task while any spare capacity is utilized by the secondary task (Kahneman, 1973). As the cognitive load for the primary task increases, there will be observed decrements in secondary task performance when both are performed concurrently (Kahneman, 1973). Thus, dual-task costs are defined as the reduction in performance on each task individually (i.e., single-task condition) to two tasks performed simultaneously (i.e., dual-task condition). Using this approach, listening effort can be objectively measured among older adults. Gosselin and Gagné (2011) conducted a dual-task study, wherein hearing-intact younger and older adults performed a closed-set sentence recognition test simultaneously with a vibrotactile pattern recognition test. They showed that older listeners required more listening effort to identify speech in noise. Tun, McCoy, and Wingfield (2009) compared older adults with mild-to-moderate hearing loss who exhibited greater performance cost when performing a visual target tracking task and auditory memory recall concurrently in comparison to peers and younger adults with normal hearing thresholds. These patterns illustrate that older adults must allocate more cognitive resources to perform a listening task when performed concurrently with a secondary task because listening becomes more effortful, which can be exacerbated with hearing loss.

A methodological limitation of the aforementioned studies is the use of single-speaker discourse or simple audiological evaluations. Notably, such assessment techniques are not designed to evaluate everyday listening conditions that reflect multiple speakers and competing noise, both of which reduce speech understanding (CHABA, 1988). It is unclear whether these difficulties are due to sensory distortions, or cognitive ability to interpret a distorted signal. Auditory processing in a noisy environment is divided into the acoustical properties of a stimulus (i.e., bottom-up) and reliance on stored auditory representations based on prior knowledge (i.e., top-down; Bregman, 1990). The interplay of cognitive and auditory factors in a multitalker situation was first described by Cherry (1953) as the “cocktail party” situation. In an everyday multitalker environment, listeners use auditory processing to spatially locate the sound source from different locations. The listener must also rely on cognitive processes to attend to the target speech stream and ignore distracting sounds. When more than one talker is present, additional cognitive resources are recruited. On a cognitive level, the listener must engage in selective attention (i.e., attend to a single talker), divided attention (i.e., attend to multiple auditory streams simultaneously), inhibition (i.e., ignore irrelevant speech), and spatial attention switching (i.e., attentional resources are shifted between different spatial locations). Researchers have shown that older adults exhibit deficits in divided attention and inhibition (Hasher & Zacks, 1988; Pashler, 1993), while selective attention is less affected by age (Verhaeghen & Cerella, 2002). On a perceptual level, the ability to selectively attend to multiple talkers is based on the features of the auditory scene (Murphy et al., 2006). Thus, age-related decline in auditory and cognitive factors can produce difficulty in understanding speech in complex listening situations (Pichora-Fuller, 1997; 2003b).

Researchers have proposed that disruptions to speech processing in multitalker contexts stem from differences in processing auditory cues associated with advancing age. Naturally, the location of each talker will vary; as such, the auditory scene provides cues to the listener that aid in spatially segregating the talkers (Murphy et al., 2006; Cherry, 1953). The auditory cues implicated in multitalker speech perception can be divided into monaural and binaural factors (Ericson, Brungart, & Simpson, 2004). Specifically, monaural factors include SNR, the number of competing talkers, voice characteristics, and target-to-masker ratio (Ericson et al., 2004). In contrast, binaural factors involve the apparent spatial location of the talkers and the listener's a priori information about the listening task (Ericson et al., 2004). Both monaural and binaural cues can facilitate speech perception in noise in order to spatially separate a target from a masker. When the auditory signal is spatially segregated from a masker it creates an interaural level difference (i.e., difference caused by the head shadow) and an interaural time difference (i.e., difference due to distance a sound must travel to each ear; Bronkhorst, 2000; Blauert, 1997). Cherry (1953) argued that spatially separating a target from a masker can improve target recognition. As a result, there is a release from energetic masking (i.e., reduced neural competition between a target and masker) and release from informational or perceptual masking (i.e., less competition in higher-order processes; Durlach et al., 2003; Li et al., 2004; Watson, 1987). Murphy and colleagues (2006) demonstrated that older adults showed reduced accuracy in comprehension and/or memory about a dialogue when the spatial separation of two-talkers in babble were closer together than further apart compared to younger adults. Age-dependent differences in monaural and binaural processing in older adults with normal hearing levels may reduce the release of a target from masking with spatial separation (Koehnke & Besing, 2001; Grose, 1996) and explain why older adults are disproportionately affected by understanding speech in spatially distributed multitalker situations (Singh, Pichora-Fuller, & Schneider, 2008). Singh's study (2008) involved a real spatial separation design wherein a target sentence was physically separated from maskers in three spatial locations (i.e., left, right, and center) and the probability that the target sentence would be presented at each location was manipulated to examine word identification accuracy. They found that older adults performed worse than younger adults, however both age groups performed best when the location of the target sentence was certain. Furthermore, declines in processing binaural cues can reflect loss of neural synchrony with increasing age, apparent in early stages of presbycusis (Grose, Poth, & Peters, 1994; Pichora-Fuller & Schneider, 1991, 1992).

In sum, age-dependent decrements in perceptual and cognitive factors are involved in speech understanding, particularly under noisy or multitalker contexts. Age-related discrepancies between younger and older listeners in multitalker situations may reflect limited cognitive capacity and an inability to use auditory cues. Together, these factors make listening more effortful and challenging. What remains less well understood is how auditory and cognitive aging affect listening ability in more dynamic, everyday situations such as walking while talking. Past studies of audition generally involve testing under seated conditions in a sound-attenuated environment, thus lacking generalizability to real life situations. Given the known association between hearing loss and mobility decline (Lin et al., 2011; Lindenberger & Baltes, 1994; Lövdén, Ghisletta, & Lindenberger, 2004), it is expected that performance would be worsened in at least one of these domains when both are performed simultaneously. The next section reviews the evidence suggesting that there is increasing cognitive involvement in motor function with advancing age.

Cognitive Control Processes in Motor Aging

Analogous to auditory aging, cognitive decline is a determinant of walking difficulty commonly observed in older adults (Binder, Storandt, & Birge, 1999). Walking represents a complex task, governed by higher order cognitive mechanisms and executive functions (Hausdorff, Yogev, Springer, Simon, & Giladi, 2005). Even simple, steady-state walking performance has been described akin to game-catching performance, an action that involves planning, estimation, and real-time adjustments (Hausdorff et al., 2005). The maintenance of postural control while walking requires coordination and integration of proprioceptive, vestibular, and visual systems, and the execution of corresponding movement through the lower limbs and trunk (Woollacott & Jensen, 1996). Physiologically, aging negatively affects balance and gait through physical changes such as reduced strength, muscle mass, bone density, and selective atrophy of the central nervous system associated with motor function (Butler, Druzin, & Sullivan, 2006). Walking can be characterized by alternating leg movements that yield a single- and double-support phase (Lajoie, Teasdale, Bard, & Fleury, 1996). During walking, the center of gravity is held in front of a person's base of support (Lajoie et al., 1996). With age, cognitive demands for walking increase which negatively affect processes necessary for postural stability (Brown & Woollacott, 1998). Speilberg (1940) first systematically described age-related gait changes which included slower walking velocity, lower cadence, shortened stride, and unbalanced coordination between lower and upper extremities. Stable gait reflects control and balance during walking, however increases in gait variability can result in unsteadiness, , and falls risk (Maki, 1997). Falls among older adults are a major source of hospitalizations and mortality (Newman et al., 2006). Furthermore, falls that do not lead to serious injury can nevertheless produce a fear of falling and result in the loss of independence and quality of life (Shumway-Cook, Baldwin, Polissar, & Gruber, 1997a; Tinetti, Mendes de Leon, Doucette, & Baker, 1994). Gabell and Nayak (1984) argued that walking performance may serve as an indicator of disability or falls risk. It is found that step length and stride time are indicators of *gait patterning*, whilst gait velocity, stride length variability, stride time variability, stride width, and double-support time are considered indicative of *balance* and are predictors of falls (Butler et al., 2006; Craik, 1989; Hausdorff, Rios, & Edelberg, 2001).

A large corpus of studies that investigated the interplay between cognitive processes and gait have relied on dual-task methodology to examine the simultaneous performance between cognitive and motor tasks (Hausdorff, Schweiger, Herman, Yogev-Seligmann, & Giladi, 2008; Kemper, Herman, & Lian, 2003; Li, Lindenberger, Freund, & Baltes, 2001; Verrel, Lövdén, Schellenbach, Schaefer, & Lindenberger, 2009). In earlier work, researchers focused on attentional demands in postural control by examining age-related differences in posture during simultaneous performance of a simple secondary task (Woollacott & Shumway-Cook, 2002). Lajoie, Teasdale, Bard, and Fleury (1993; 1996) revealed that standing and walking requires more cognitive resources than sitting in a chair. Notably, the researchers found slower reaction times on a simple auditory task for both younger and older adults while standing and walking than under sitting conditions. In addition, researchers noted that older adults showed slower walking speed and reduced stride length than younger adults. Although Lajoie and colleagues

(1996) did not show an effect of the simple auditory task on gait, Chen and colleagues (1996) found that older adults had greater difficulty avoiding obstacles when their attention was divided during a complex, vocal reaction time test compared to younger adults. Therefore, as the secondary task becomes more demanding, the age-related effect on gait generally increases (Woollacott & Shumway-Cook, 2002). Subsequent studies extended these early findings using novel and complex combinations of cognitive tasks and walking that represent a higher degree of ecological validity. For example, Lindenberger, Marsiske, and Baltes (2000) asked young, middle-aged, and older adults to perform a memory encoding task in conjunction with sitting, standing, and walking on tracks of different path complexity. The researchers found that with advancing age there were greater dual-task costs in memory accuracy while walking in comparison to when standing or sitting. Furthermore, older adults showed reductions in walking speed and walking accuracy while concurrently encoding, particularly under complex tracks. Thus, under complex secondary tasks, there is an evident trade-off between reduced cognitive performance and walking, whereby locomotion requires more resources with advancing age, and cognitive costs emerge. These age-related, dual-task costs in cognitive performance have been consistently found in subsequent studies that utilized memory tasks in combination with walking (Li et al., 2001; Verrel, 2009; Yogev-Seligmann et al., 2010). In addition, these performance costs are exacerbated in elderly idiopathic fallers (Springer et al., 2006).

Researchers have also focused on other relevant secondary tasks, such as talking. Walking while talking (WWT) paradigms examine the causal effects of attention on mobility similar to past dual-task studies, but more importantly they provide greater ecologically validity by using cognitive tasks that mimic everyday function (Holtzer et al., 2011). Clinicians have reported that frail elderly patients who stop walking when engaged in a conversation are more likely to fall than those who can maintain walking while responding to questions (Lundin-Olsson, Nyberg, & Gustafson, 1997). Verghese and colleagues (2007) instructed healthy older participants to walk while reciting alternate letters of the alphabet, and found that older adults displayed more disturbed gait including reduced velocity, cadence, and step length when talking and walking, compared to only walking. The authors concluded that task prioritization for walking was evident in older adults. The same research team conducted a functional near-infrared spectroscopy (fNIRS) study using a walking while reciting paradigm, and reported that older adults may underutilize the prefrontal cortex needed to coordinate attentional resources between cognition and walking while younger adults are able to manage the increased cognitive demands (Holtzer et al., 2011). Using a naturalistic virtual reality paradigm, Neider and colleagues (2011) examined dual-task WWT performance in younger and older adults who were asked to cross an intersection while undistracted, listening to music, or engaged in a cell phone conversation. Older adults were slower at street crossing and were more likely to be involved in a collision with a vehicle when distracted compared to younger adults. A limitation of this study is a lack of detailed gait analyses to provide additional evidence of gait instability or fall risk. Nevertheless, this study is one of few that have examined dual-task walking with a concurrent listening task and high ecological validity.

Altogether, the dual-task costs in gait and secondary task performance in the literature of cognitive aging provide evidence for the model of selection, optimization, and compensation (SOC) proposed by Baltes and Baltes (1990). The SOC posits that an individual must select a goal, find ways to optimize goal-relevant means, and compensate for losses to maintain behaviour or performance. In the framework of cognitive and sensorimotor tasks, the SOC model would predict higher dual-task costs in older adults than in young adults when faced with concurrent cognitive task demands and increased sensorimotor challenge, due to reduced general resource capacity. Furthermore, older adults would select, or allocate, resources toward maintaining their stability, to prioritize sensorimotor function at the cost of cognitive performance. This prioritization of mobility or the "posture first" principle is the notion that elderly people will prioritize postural control, while younger adults will use a "cognitive first" principle and prioritize cognitive performance (Li et al., 2001; Shumway-Cook, Woollacott, Kerns, & Baldwin, 1997b). Older adults tend to prioritize sensorimotor function likely due to avoidance of falls, fear of falling, and decreased mobility function. Li, Krampe, and Bondar (2005) argued that the adaptive allocation of resources warrants the consideration for ecologically relevant walking or postural control in the elderly compared to younger adults. An ecological assessment of dual-task performance would better elucidate the way older adults allocate their attention between listening and walking tasks in their everyday activities.

To summarize, emerging dual-task research provides a clear link between cognitive performance and gait; two domains that increases in interdependence with advancing age (Amboni, Barone, & Hausdorff, 2013). The use of ecologically valid dual-task paradigms such as WWT offers greater insight into resource allocation conflicts between cognition and walking in everyday contexts. However, there is a paucity of research that uses naturalistic tasks that reflect daily activity. Moreover, the dual-task studies available in the literature focus almost exclusively on lower limb walking parameters, neglecting activity in the upper body during walking. Researchers fail to acknowledge how the upper body may contribute to regularity of whole body motion under divided attention. Normal walking consists of the use of upper limbs to perform daily activities, such as carrying objects. Additionally, on a daily basis walking and auditory processing are performed in concert. To our best knowledge, there is no study that has empirically investigated the effect of cognition on whole body motion and audition in a dual-task paradigm, particularly in a naturalistic context. Moreover, it is presently unclear how the posture first principle will fit into the hearing-mobility interaction. To shed light on these matters, the use of an ecological valid dual-task paradigm that examines whole-body locomotion may further elucidate the role of cognitive factors involved in gait variability and falls risk under concurrent auditory challenge.

Theoretical Approaches Linking Hearing Loss and Mobility Decline

There is abundant epidemiological or associational evidence of increased cognitive involvement in both hearing and locomotion with increasing age (Anstey, Stankov, & Lord, 1993; Baltes & Lindenberger, 1997; Lindenberger & Baltes, 1994; Butler et al., 2006). For example, it is well-documented that executive functions, hearing, and mobility show linear decline during adulthood and accelerated decline in old age. Early work by Lindenberger and Baltes (1994) from the Berlin aging study (BASE; Baltes & Mayer, 1999) found that auditory and visual acuity combined accounted for 93.1% of the variance in intelligence (measured as processing speed, memory, reasoning, fluency, and knowledge) in old and very old adults. When gross motor functions were considered, Lindenberger and Baltes (1997) found that balance-gait measures accounted for 82.6% of the variance in general intelligence respectively, in old and very old adults. Together, these findings show an increased covariation among sensory, motor, and intellectual abilities (Li & Lindenberger, 2002). The most prominent interpretation of these findings is the common cause hypothesis, which posits that there is a common factor such as general neurodegeneration that affects sensory, sensorimotor, and intellectual decline (Lindenberger & Ghisletta, 2009; Lindenberger & Baltes, 1994). Lindenberger and Ghisletta (2009) compared the original cross-sectional BASE findings with subsequent tests of the common cause model using longitudinal data, finding that the variance accounted for decreased substantially. They proposed an alternative explanation, namely the cognitive permeation hypothesis, which may co-occur with general neurodegeneration (Li & Lindenberger, 2002).

The cognitive permeation or cognitive compensation hypothesis argues that sensory and sensorimotor functions become more effortful and thus require greater cognitive resources to compensate for decline with increasing age (Lindenberger, Marsiske, & Baltes, 2000). The notion of cognitive compensation in older adults is an early idea that has been well-accepted in several models of cognitive and sensory aging (for a review, see Grady, 2012; Park & Reuter-Lorenz, 2009). By this view, in response to age-related neural challenges, executive functions are recruited adaptively to meet the challenges of cognitively demanding tasks (Reuter-Lorenz & Cappell, 2008). Therefore, as sensory and sensorimotor functions decline with age there is a negative association with cognitive performance. As evidenced by dual-tasks, there are larger declines in cognitive or sensory/sensorimotor functions in older adults compared to younger adults. This indicates that with advancing age there is more competition for scarce resources, and in turn, compensatory tradeoffs (Li & Lindenberger, 2002). Neuroimaging techniques provide strong support for the notion of cognitive compensation in aging, including the overactivation of the prefrontal cortex and greater bilateral activation observed in older adults to compensate for neural changes and to meet task demands (for a review, see Seidler et al., 2010).

Current Study: Walking While Listening

Despite the research separately linking auditory and motor aging with cognition, there is a lack of research that has considered how limited cognitive resources are distributed between audition and gait under divided attention in younger and older adults. To address this gap in the literature, the present study was designed to experimentally investigate age-related differences in concurrent walking and listening. We adapted the dual-task paradigm to reflect more of an everyday cognitive task similar to talking to a friend in a group of people. Thus, the current cognitive auditory task was an extension of the design used by Singh and colleagues (2008) that involved multiple talkers. This study used a real spatial separation design, wherein three sentences were presented simultaneously from three evident spatial locations (right, left, and center). In addition, a priori information regarding the location of the target utterance (certain or less certain target location probability) from three spatial locations was manipulated to explore the role of attention and the effect of increased auditory challenge. Participants were instructed to report components from the target sentence and word recognition accuracy was measured. We paired the cognitive auditory task with treadmill walking to examine the effects of dual-tasking on listening and gait in younger and older adults with normal hearing. Participants completed five conditions: walking only, listening only (under certain and less certain location probability), and walking while listening (under certain and less certain location probability) in a complex, simulated street crossing environment using virtual reality (VR). The VR was used to provide a stimulating and ecological testing environment. Furthermore, we addressed the lack of studies measuring whole body motion and dual-task gait by analyzing head and trunk angles in addition to standard lower body spatiotemporal gait variables. Based on the cognitive compensation theory, it was hypothesized that older adults would exhibit greater dual-task performance costs compared to younger adults, due to competition for scarce cognitive resources between both domains. Furthermore, it was expected that older adults would be disproportionately affected by increased uncertainty of the target utterance location. Finally, consistent with the posture first principle, it was hypothesized that older adults would allocate more cognitive capacity towards stable walking over cognitive performance, whereas younger adults would more evenly distribute their attention between listening and walking.

Method

Participants

Seventeen healthy young adults (aged 18 – 32, *M* = 25.53, *SD* = 3.59, female *n* = 13) and twelve healthy older adults (aged 63 – 76, *M* = 66.83, *SD* = 3.54, female *n* = 9) with normal hearing acuity participated in this study. Hearing acuity was determined using standard audiometric pure-tone testing. Young adults' pure-tone average (PTA) thresholds aggregated across 0.5, 1.0, and 2.0 kHz ranged between -3.33 to 10.00 dB/HL (*M* = 3.23, *SD* = 2.97) and older adults' PTA thresholds ranged from 3.33 to 18.33 (*M* = 8.82, *SD* = 4.58). The mean audiometric thresholds for the left and right ear in young and older adults are shown in Figure 1. The average number of years of formal education reported by younger adults was slightly higher (*M* = 17.53, *SD* = 2.15) than older adults (*M* = 15.58, *SD* = 2.47). All participants were native English speakers (i.e., learned English prior to the age of 5 in an English speaking country) and had normal or corrected-to-normal vision.

Participants were recruited using advertisements posted in community centres, an ad in the local senior paper, nearby hospitals and universities, and from a participant database pool from the Toronto Rehabilitation Institute. All participants underwent an initial telephone screening interview to ensure eligibility for the study. The exclusion criteria consisted of any hearing impairment (i.e., hearing thresholds >25 dB up to 3.0 kHz), asymmetrical hearing (>15 dB right/left ear difference at more than two adjacent frequencies), use of hearing aids or assistive walking devices, vision impairment, colour blindness, any pre-existing major health concern or psychiatric disorders, or mild cognitive impairment as indicated by the Montreal Cognitive Assessment (MOCA: <26 / 30). This study was approved by the University Health Network Research Ethics Board and all participants provided informed consent.

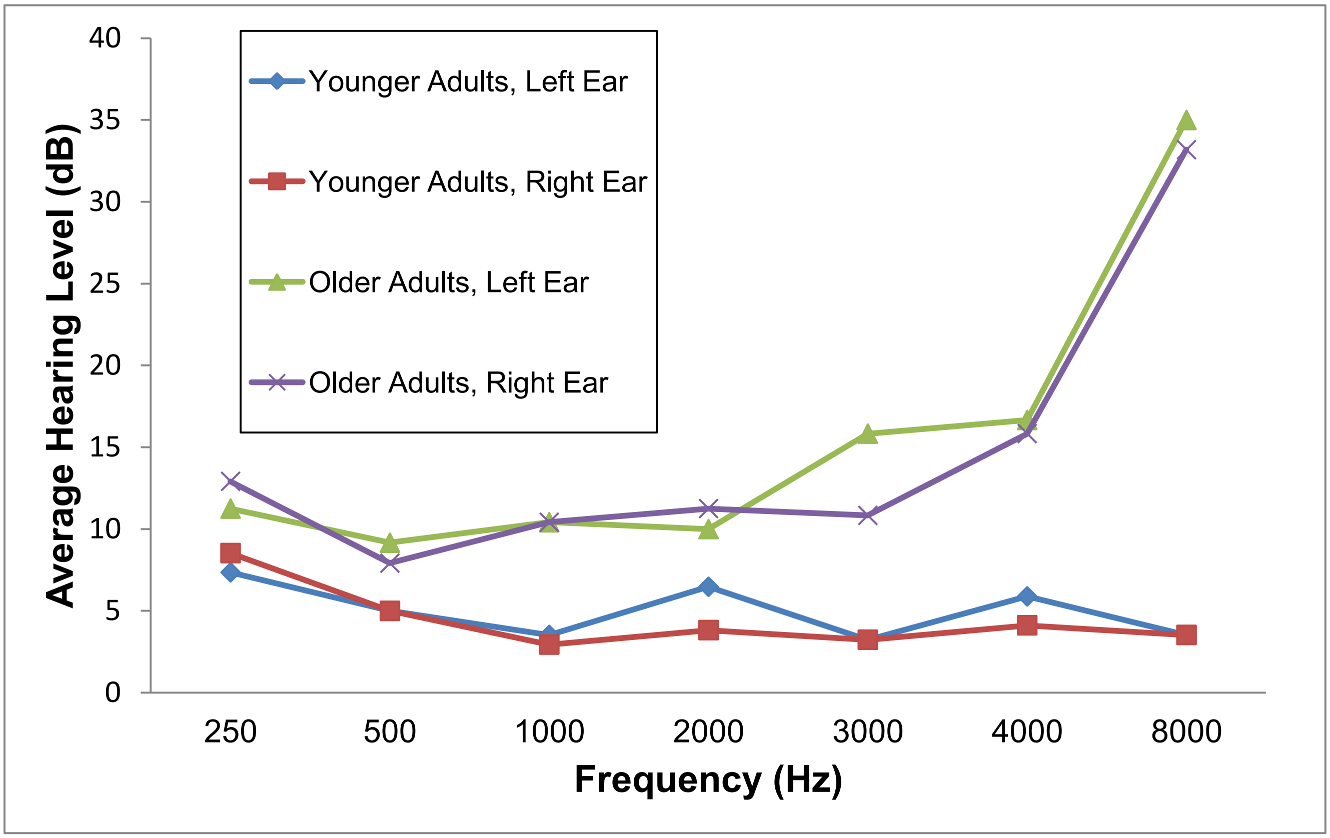


Figure 1. The mean audiometric thresholds in the left and right for younger and older adults.

Materials and Procedure

Participants initially completed a series of neuropsychological, sensory, and sensorimotor background measures prior to experimental tests in order to more fully describe their cognitive, sensory, and physical characteristics.

History Questionnaire. This questionnaire consists of 42-items that measured background information regarding the participants' chronological age, ethnicity, education, employment, and overall health (see Appendix A).

Montreal Cognitive Assessment. The Montreal Cognitive Assessment (MoCA; Nasreddine et al., 2005) is a 30-item screening tool used to detect mild cognitive impairment in the elderly. It measures visuospatial abilities using copying of a three-dimensional cube (1 point) and clock-drawing (3 points). Short-term memory is assessed with free recall of five words presented in two learning trials (5 points). Executive functions are measured with a trail-making letter-number alternating task (1 point), two-item verbal abstraction task (2 points), and a verbal fluency task (1 point). Attention, concentration, and calculations is measured with a tapping-task with a target letter (1 point), serial subtraction task (3 points), and a digit forward and backward task (2 points). Language is measured with an animal-naming task of low-familiarity (3 points) and repetition of two complex sentences (2 points). Lastly, orientation to time and place are evaluated (6 points). The points are summed and scores less than 26 are indicative of mild cognitive impairment. Participants that have 12 years of education or less are provided with one additional point. The MoCA has good internal consistency (Cronbach's $\alpha = 0.83$, Nasreddine et al., 2005).

Letter-Number Sequencing. The Letter-Number Sequencing (LNS; Wechsler, 1997) is a subtest from the Wechsler Adult Intelligence Scale – Third Edition (WAIS-III) that assesses attention and working memory. It is a 21-trial test comprised of number and letter sequences (ranged from 2 number-letter combinations to 8) that increases in length by 1 span after 3 trials. The examiner verbally presents a sequence and the examinee must repeat the sequence but report numbers first in ascending order, followed by letters in alphabetical order. For example, the sequence “T-9-A-3” would be correctly reported as “3-9-A-T” by the examinee. The examinee must correctly repeat at least 1 of 3 consecutive trials in order to advance to the longer combinations of numbers and letters. If the examinee fails to correctly report 3 consecutive trials then the test terminates. All correctly reported sequences are summed to determine an individual’s digit span length. High scores on the LNS are indicative of a larger span length in working memory. The LNS has shown to have high reliability (Cronbach’s α = 0.82, Wechsler, 1997).

Digit-Symbol Coding. The Digit Symbol Coding (DSC; Wechsler, 2008) is a subtest of the Wechsler Adult Intelligence Scale (WAIS-IV) that measures processing speed. There are 9 digit-symbol pairs, the examinee is presented with a list of digits and must write down the corresponding symbol underneath each digit as quickly as possible for an allotted time of 2 minutes. All correctly written symbols are summed, wherein higher scores correspond to faster cognitive processing speed. The DSC has been found to have high split-half test reliability (Cronbach’s α = 0.93, Lichtenberger & Kaufman, 2013).

Colour-Word Stroop Test. The Colour-Word Stroop Test (CWST; Stroop, 1935) is a classical measure of cognitive interference. In the control condition, the examinee must read aloud the ink colour (blue, green, tan, or red) of printed asterisks. In the experimental condition, the examinee must verbally report the ink colour of incongruently matched colour words. In the latter condition, the examinee must inhibit the meaning of the printed colour word. Examinees are given 2 minutes to complete each condition. A difference score was calculated by averaging the amount of correctly reported items by time (seconds) for the control and experimental condition and subtracting the difference. The final score corresponds to an individual's resistance to interference, with high scores indicative of better performance. The CWST has been found to have relatively high test-retest reliability for the control condition and experimental condition (0.79 and 0.71, respectively; Jensen, 1965).

Delis Kaplan Executive Function System – Trail Making Test. The Delis Kaplan Executive Function System – Trail Making Test (DKEFS – TMT; Delis, Kaplan, & Kramer, 2001) is a subtest used to measure a diversity of executive functions. There are five conditions: visual scanning, number sequencing, letter sequencing, number-letter sequencing, and motor speed. Visual scanning requires the examinee to cancel all the 3's presented in an array of numbers and letters. Number sequencing involves connecting lines between numbers within circles in ascending order. Letter sequencing involves connecting lines between letters in alphabetical order. Number-letter switching requires the examinee to connect numbers and letters in an alternating manner in ascending numerical and alphabetical order. Lastly, motor speed consists of drawing over dotted lines. Examinees are instructed to complete each condition as quickly as possible and the examiner records the reaction time. Number-letter sequencing is the experimental condition that is used to assess flexibility of thinking, while the other four conditions are controls. A final score is calculated by subtracting the average of condition 2 (number sequencing) and 3 (letter sequencing) from condition 4 (number-letter sequencing). Low scores on the DKEFS - TMT correspond to better performance on flexible thinking. The internal consistency for the DKEFS – TMT is fairly high (ranged from 0.57 – 0.81; Shunk, Davis, & Dean, 2006).

Audiometric Screening. Audiometry was performed by a trained examiner with the Grason-Stradler – 61 clinical audiometer in a sound-attenuating booth using Sennheiser headphones. Daily calibration and monitoring of ambient noise was performed to ensure quality of testing. All participants were tested for pure-tone hearing thresholds from 0.25 to 8.0 kHz, with 1 kHz at 40 dB as the first threshold tested. Testing began in the better ear as indicated by the examinee. If not specified, testing began with the right ear. The examinee was presented with tones in a range of frequencies and intensities and used a hand-held button-press to indicate when they heard such tones. After successful tone detection, the dB presentation level of a tone was reduced by increments of 10 dB, whereas failure to detect a tone increased the presentation by 5 dB. The lowest dB presentation level of a tone that was successfully detected three times was the threshold identified for each frequency. The PTA threshold for each ear was calculated by aggregating the minimum tone detected at thresholds 0.5, 1.0 (reliability check), and 2.0 kHz. The final value is indicative of the PTA for the better ear, wherein lower values suggest better hearing acuity.

Word-in-Noise Test. The Word-in-Noise Test (WIN Test; Wilson, 2003) was developed to examine the ability to understand words presented in multitalker babble. There are 70 monosyllabic words presented by a female speaker in seven SNRs of babble that ranged from 24 dB S/B to 0 dB S/B in 4 dB decrements after 5 words. Half of the words are presented to one ear and the other half presented to the other ear. The examinee must verbally report the final word in the sentence structure “say the word __”. If the examinee failed to correctly report a word within each SNR the task terminated until they have completed the final 5 words within that SNR. The presentation level of the words (dB) is individually determined for each ear for all participants. PTA $\leq$ 40 dB/HL will set the babble presentation at 80 dB, PTA > 40 to 59 dB/HL corresponds to 90 dB, and PTA $\geq$ 60 dB/HL is not administered as no data is available on individuals with such thresholds. All correct responses are summed and the metric of interest is the SNR at which recognition performance is 50%. The final value corresponds to 50% correct word recognition threshold.

Early Treatment Diabetic Retinopathy Study. The Early Treatment Diabetic Retinopathy Study (ETDRS; Early Treatment Retinopathy Study Research Group, 1985) measures far-sighted visual acuity. Examinees are instructed to identify letters on an eye chart from 4 meters. Monocular vision is tested by instructing examinees to cover one eye at a time and verbalize the letters. The number of letters that are correctly identified from specified distances are summed, wherein higher letter scores correspond to better far visual acuity.

Activities-Specific Balance Confidence Scale. The Activities-Specific Balance Confidence Scale (ABC Scale; Powell & Myers, 1995) is a 16-item self-report questionnaire that measures confidence in balance in a range of activities. Examinees indicated their level of confidence using a percentage-scale that ranged from 0% (no confidence) to 100% (complete confidence). If examinees had not performed such activities they were asked to imagine performing that activity or if they used a form of assistance (e.g., walking aid) they must rate their confidence with the use of external supports. The total ratings are added and averaged across the 16-items to obtain a final score. Scores < 67% is suggestive of falls risk in older adults and predictive of future falls (Lajoie & Gallagher, 2004).

Dynamic Gait Index. The Dynamic Gait Index (DGI; Shumway-Cook & Woollacott, 1995) was developed to examine the ability to modify gait in response to altering task demands in older adults. There are eight tasks that measure stable walking, walking while changing gait speed, walking while moving the head, walking over and around obstacles, pivoting during walking, and climbing stairs. The examinee is instructed to walk on a 20-foot path, wherein performance across tasks is assessed on a 4-point scale (3 = normal, 2 = mild impairment, 1 = moderate impairment, and 0 = severe impairment) based on the examiner's observation. The maximum score on the DGI is 24 points and scores ≥ 19 is associated with gait impairment and falls risk (Shumway-Cook et al., 1997a).

Timed Up & Go Test. The Timed up & Go Test (TUG Test; Podsiadlo & Richardson, 1991) has been used to examine gait speed, balance, and functional ability in older persons. The examinee must sit in a standard armchair, with their back against the chair and arms on the chair's arms. On the command "Go," the examinee rises from the chair, walks in a normal gait speed to a line in 3 meters, turns around at the line, walks back to the chair and sits down. The examiner uses a stopwatch to measure the time it takes to complete the test from "Go" to the time it takes for them to become fully seated again. This test is repeated twice and the average of the two tests is aggregated. Completion time > 13.5 seconds is found to be a useful predictor of risk of falls in older adults (Barry, Galvin, Keogh, Horgan, & Fahey, 2014).

Virtual Reality Street Crossing. The experimental task was conducted at the Toronto Rehabilitation Institute in the Challenging Environment Assessment Lab (CEAL) that contains a virtual reality testing pod referred to as StreetLab (Appendix B). StreetLab contains a 240°, by +15° to -90° vertical and curved field-of-view LED projection system from the floor to ceiling. A high resolution, three-dimensional virtual environment of downtown Toronto is visually projected using 6 (1920 X 1200 native resolution) projectors. Seven speakers and one sub-woofer are used to produce a realistic audio soundscape to provide a multi-sensory and fully-immersive experience. The environment was programmed to depict daytime, with no vehicular traffic or pedestrians. A linear treadmill (Woodway LOKO model) interface with no handrails was positioned at the base of the testing pod. The allowable speed ranged from 0 to 1 m/s and was actively controlled through a hand-held joystick by the participant. Each participant was equipped with a safety harness that was attached above their head to an anchor.

At the onset of each walking trial, participants were positioned at the sidewalk of a major Toronto boulevard. Participants were informed when to begin walking and used a joystick to activate the treadmill to stimulate a street crossing. Once participants reached the end of the boulevard, the experimenter informed the participant to stop walking. The visual display was then reset to the original starting point of the boulevard to prepare for the next trial. In single-task walking conditions, participants were instructed to perform four street crossings, and were instructed to focus on their walking. Under walking while listening conditions, participants completed 4 – 5 street crossings, depending on how quickly the participant was able to complete the listening task, and were instructed to perform walking and listening equally well, to the best of their ability.

Motion Capture System. An active marker LED system (Phoenix Technology Inc. VZ4000) was used to evaluate whole-body locomotion. Two active markers each were positioned on the head, sternum, and waist, while eight markers were placed on the dorsal portion of each foot. The use of multiple markers for each body segment ensured redundancy in the event that one marker signal was obstructed. . In addition, three active markers were arranged on the treadmill to create the x, y, and z landmarks. Prior to the onset of each testing session, these landmarks were calibrated. All landmark and body markers were actively read by three motion capture cameras placed overhead, in front of the participant. Participants underwent an initial full body static shot to identify all the markers positioned on the body. During this time, participants were instructed to maintain an upright, stable posture directly in front of the motion capture cameras. The sampling frame rate was 100 Hz. The following upper body gait parameters were measured: average head pitch and roll, average trunk pitch and roll, peak head pitch and roll, peak trunk pitch and roll. Pitch is the amount of rotation front-to-back and roll is the degree of rotation side-to-side. The average was calculated by aggregating the angle at each time point of a signal. Peak was calculated by the absolute peak of the maximum and minimum. Head parameters were measured from the degree of rotation between the head and sternum, while trunk parameters were measured from the degree of rotation between the sternum and waist. The full body static shot created a 0° reference plane for the pitch and roll rotations wherein all rotational deviation away from this reference plane was calculated for the upper body across walking conditions. For instance, in pitch, all rotation forward would be considered a positive degree rotation from 0° while all rotation backward can be considered a negative degree rotation from 0°. Large deviation from the 0° alignment is considered to be maladaptive. There were also several lower gait parameters measured: average step width (the width between the heel contact of the current footfall to the heel contact of the previous footfall on the opposite foot), average stride length (the length between the toe off from the previous footfall and the heel contact of the current footfall of the same foot), cadence (the average number of steps taken in a minute), velocity (distance over time), average stride time (time measured in seconds from the heel contact and toe off on the same foot).. It is considered that larger step width, stride time, cadence, and velocity, and smaller stride length are maladaptive. All lower limb gait parameters were averaged across the left and right foot. These variables of interest were chosen to observe the activity of lower and upper body during walking. In addition to affording a more complete assessment of locomotion, the inclusion of upper body markers (e.g., head angles) was informative in this particular study due to the requirements of spatial listening.

Auditory Word Recognition Task. The word recognition task was adapted from the materials used by Singh and colleagues (2008). The stimuli comprised of sentences from the coordinate response measure (CRM) corpus, spoken by three male talkers (Ericson et al., 2004; Bolia, Nelson, Ericson, & Simpson, 2000). The CRM was originally designed to examine speech intelligibility with a noise masker, however its structure allows for use in multitalker tasks (Ericson et al., 2004). The sentences contain the structure “Ready, [callsign], go to [colour][number] now.” The sentences contain all potential combinations of eight call signs (arrow, baron, charlie, eagle, hopper, laker, ringo, tiger), four colours (red, blue, green, white) and eight numbers (1 – 8). All sentences were presented at 60 dB. In the listening task, the main dependent variable was word identification accuracy.

In the auditory word recognition task, three sentences (one target, two maskers) were presented simultaneously from three apparent spatial locations (left, center, right). The simulated spatial location of the sentence in front was presented at 0° azimuth, while sentences presented from the left and right were positioned at ± 90° azimuth in the horizontal plane. On a given trial, the target callsign and maskers varied, with regards to the colour and number. At the start of each trial, the target callsign was visually presented in front of the participant on the projection screen, for example, “Callsign: Charlie.” This cued the participant to listen for the sentence that contained the target callsign amongst the three sentences. The participant was instructed to verbally report the colour and number contained in the sentence with the target callsign. The response was manually recorded by an experimenter inside StreetLab on a Samsung tablet. Once the participant’s response was inputted on the tablet, feedback “Correct” or “Incorrect” was visually depicted on the projection screen in front of the participant after every trial.

The location certainty of the target sentence was manipulated in the auditory task. Prior to each block, participants were informed of the probability that the target callsign would be presented from the front, left, or right. Two levels of location certainty were used in this experiment: In the high certainty condition, the target callsign was presented from the front in 100% of the trials (0-100-0). Participants were instructed as such, and to focus their attention to the sentence in front. In the variable certainty condition, the target callsign was presented from the front ≤75% of the time. Participants were informed that there was ≤75% chance that the target callsign would be presented from the front, and ≥25% chance that the target would be presented from the left or right. Across all single- and dual-task listening blocks, participants were instructed not to move their head side-to-side. During single-task listening blocks participants stood on the treadmill and the visual display was static showing the starting position for street crossing with a “no crossing” pedestrian signal.

Design

A factorial design was utilized to examine listening and gait measures. In the cognitive auditory task, two independent variables were systematically manipulated: task (single- vs. dual-task) and location certainty (2 location probability specifications: certain vs. uncertain). Word identification in the cognitive auditory task was measured between age groups. In the walking task, cognitive load was manipulated with respect to task type and location certainty. Upper body and lower limb gait parameters were measured. Together, there were five experimental conditions: single-task walking, single-task listening 100%, single-task listening ≤75%, dual-task 100%, and dual-task ≤75%. There was a total of 10 blocks. In 4 blocks, single-task listening under certain and less certain location probabilities is performed twice. In another 4 blocks, the dual-task was performed under certain and uncertain location probabilities. All listening blocks consisted of 20 trials.[1] Lastly, 2 blocks consisted of single-task walking, wherein the participant completed four street crossings. The order of testing between the two presentation methods (single- vs. dual-task and both location certainties) was counterbalanced. All participants completed every condition.

General Procedure

All participants were individually tested in two sessions. In the first session, participants completed the neuropsychological, sensory, sensorimotor, demographic, and history questionnaires. Participants who met the criteria were scheduled to return for a second session on a separate day, to complete the dual-task experiment. Each visit was completed in approximately 2.5 – 3 hours. At the start of the second visit, participants were familiarized with StreetLab and the treadmill. Each participant was equipped with safety gear and motion capture markers were fitted. A demonstration of the joystick to each participant was given. Participants first completed 5 practice blocks, 4 of which consisted of 10 trials of single-task listening (under 100% and ≤75% probability) and walking while listening (under 100% and ≤75% probability), as well as 1 block of two street crossings in single-task walking. Afterwards, participants completed 10 experimental blocks of walking only, listening only, and walking while listening. Upon experiment completion, participants were debriefed and remunerated with $50 and $14 for travel expenses, as well as compensated an additional $10 for any extra time spent per hour of testing.

Planned Statistical Analyses

All statistical analyses were performed using IBM SPSS statistical software version 22.

Data Screening. Prior to all statistical analyses, the data were inspected for any incorrect, missing, or out-of-range values. Word recognition accuracy and gait performance were

---

[1] A total of 7 younger adults and 5 older adults originally performed 30 trials across all listening blocks and 8 street crossings for the walking only blocks. The data were later truncated to 20 trials and 4 street crossings for these participants and subsequent test sessions were shortened to reduce fatigue in the older participants.

transformed into z-scores, and skewness and kurtosis statistics were examined to identify extreme values or outliers. In the cognitive auditory task, no such problems were detected. However, several outliers were identified in various gait parameters. Those data points were transformed to the next highest, acceptable value ($|z| < 3$ SD) for each age group.

An additional 8 younger adults and 34 older adults were screened but were not represented in the final analyses. Of these individuals, 3 younger adults and 3 older adults were not available or failed to complete the second session, 3 younger adults and 5 older adults contained corrupted kinematic data or experienced difficulties with motion capture thus prevented extraction of gait parameters, 1 young adult and 23 older adults were ineligible because they did not meet criteria for hearing acuity, 3 older adults did not meet MoCA score criteria, and 1 young adult did not continue because of poor health and balance.

Preliminary Analyses. In order to examine differences between the presentation of each condition twice (Block A vs. B), one-way analyses of variances (ANOVAs) with block as the within-subjects factor were conducted for each age group for all listening and gait conditions. In addition, mixed two-way ANOVAs were performed to examine differences between different counterbalancing orders of presented blocks (between-subjects factor) for listening performance and gait measures (within-subjects factors) for both age groups (refer to Appendix C for all counterbalancing orders). Lastly, independent samples *t*-tests were performed to examine differences between different location probability ratios. There were five probability configurations for the uncertain target location trials: 12.5-75-12.5, 17.5-65-17.5, 20-60-20, 22.5-55-22.5, and 25-50-25.

Cognitive listening data. To examine the effects of dual-tasking on word recognition accuracy, a general linear model for mixed repeated measures was used to assess main and interaction effects. Age group was examined as the between-subjects factor, as well as task-type and location probability as within-subjects factors. A 2 (age group: young vs. old) X 2 (task-type: single- vs. dual-task) X 2 (location probability: 100% vs. ≤75%) mixed ANOVA was performed. Post hoc analyses were performed using *t*-tests (with Bonferroni corrections) to (1) detect differences within conditions and (2) examine the role of age group. It was hypothesized that older adults would perform worse on word recognition accuracy than younger adults, dual-task conditions would be more cognitively challenging than single-task conditions, and reduced location certainty would be more difficult than when target location was fixed, as examined by testing main effects. In addition, it was hypothesized that older adults would be more negatively impacted by dual-task conditions than single-task, compared to younger adults, as examined by testing the 2-way interaction. As well, it was hypothesized that older adults would be more negatively affected by uncertain location probability in comparison to younger adults, which was examined by testing the relevant 2-way interaction. Furthermore, the hypothesis that older adults would be disproportionately affected by dual-task conditions and uncertain location probability in comparison to younger adults was examined by testing the 3-way interaction. Effect sizes are reported as eta square.

Kinematic data. All kinematic parameters were analyzed using Visual3D software (C-Motion, 2013). Raw data were first interpolated using a spline interpolation for missing data points at a maximum gap up to 80 frames.. Next, to reduce noise the processed data was low-pass filtered using Butterworth digital class with a cut-off frequency of 6 Hz. Subsequently, landmarks x, y, and z were created. The toe off and heel contact were extracted for each foot to create events that were fitted on the x-y trajectory. The first event and last event were removed to control for acceleration and deceleration at the onset and termination of a walking trial.

Furthermore, all spikes (i.e., points in the trajectory that did not lie on the general curve and indicate signal loss) were systematically removed by visual inspection of each walking trial. Walking trials with substantial signal loss (approximately >15%) were removed from further analyses.

To examine the effects of dual-tasking on upper and lower body gait parameters, the general linear model for mixed repeated measures was used to examine main and interaction effects. For each gait parameter, a 2 (age group: young vs. older adults) x 3 (cognitive demand: single-task, dual-task 100%, dual-task ≤75%) mixed factorial ANOVA was performed. In addition, each gait parameter was analyzed in terms of variability using the coefficient of variation (CV; standard deviation / mean). The CV is conventionally used to quantify the regulation / dysregulation of gait, and is predictive of falls risk (Hausdorff et al., 2001). Thus, a larger CV corresponds to worsened gait behaviour. Any gait variables that were not found to be significant were then subjected to a more lenient statistical analysis, that is, a multivariate analysis (MANOVA) using a similar mixed factorial design.

For both the mean level and CV measures, it was hypothesized that older adults would demonstrate worsened gait compared to younger adults overall, and that there would be a greater decline in gait performance under higher cognitive demand compared to simpler cognitive demands, tested as main effects. It was also hypothesized that older adults would prioritize walking under dual-task conditions compared to younger adults, tested as a 2-way interaction. If main and interaction effects were observed in the cognitive demand factor, polynomial contrasts were performed to detect differences among the three levels. Effect sizes are reported as eta square.

Dual-Task Costs. Additional analyses were performed using derived dual-task cost scores (DTCs) in the listening and walking data. DTCs were expressed as the difference between single-task and dual-task scores. High DTCs on the listening task indicate that participants were negatively affected by the addition of a concurrent walking task. For the gait parameters in which high values signal maladaptive gait (e.g., stride time variability), DTCs were computed as dual-task minus single-task so that large DTCs would still be indicative of maladaptive change due to increasing cognitive demands. For each derived DTC parameter, a 2 (age group: younger vs. older adults) X 2 (location certainty: 100% vs. ≤75%) mixed ANOVA was performed. In keeping with the posture first principle, it was hypothesized that older adults would not show greater DTCs in their gait performance compared to their younger counterparts.

Attentional Allocation between Tasks. Furthermore, zero order correlations were calculated to examine possible tradeoffs between listening and walking tasks in the dual-task conditions (e.g., dual-task walking 100% and dual-task listening 100%). To this end, it was hypothesized that older adults would demonstrate greater DTCs on word recognition performance compared to younger adults, but if older adults exhibited postural prioritization, they should not be strongly affected by the location manipulation as younger adults in the gait data.

Background Clinical Measures. Finally, Pearson *r* correlation coefficients were used to evaluate the experimental measures in relation with background neuropsychological and mobility scores. The significance level for all analyses mentioned above was set to .05.

Results

Preliminary Analyses

One-way ANOVAs were conducted to check for the effects of learning or fatigue between repeated blocks of the same type. For both age groups, single-task listening accuracy improved significantly from the first to second block (Fs ≥ 4.68, ps $\leq .047$), but no changes were observed for dual-task listening conditions (refer to Appendix D). One explanation for the improvement from the first to second block presentation observed under single-task conditions is that single-task conditions were performed in the first and last testing blocks thus capturing possible fatigue and novelty effects, respectively. An examination of gait parameters across two blocks of the same condition revealed that younger adults displayed decreased cadence and larger stride time variability during single-task walking from the first to second block presentation (Fs ≥ 6.47, ps $\leq .022$). As well, younger adults showed larger step width and stride time variability from the first to second block in dual-task ≤75% probability and dual-task 100% probability, respectively (Fs ≥ 5.17, ps $\leq .037$). Thus, younger adults might have habituated to the walking task, but may have gradually shifted their attention to the listening task when cognitive demands were increased. Older adults showed more aligned peak head roll, larger stride length, and larger stride time in the second than the first block presentation during single-task walking (Fs ≥ 5.05, ps $\leq .046$). In addition, older adults exhibited larger stride length in the second block presentation compared to the first in dual-task 100% probability ($F = 16.16$, $p < .002$). Overall, older adults showed more stability in their gait when moving from the first to the second block presentation. All means and standard deviations for all significant gait parameters are present in Appendix E.

In sum, the block-wise analyses revealed that in listening performance, accuracy improved from single-task Block A to B, which may reflect increased familiarity with the experimental tasks. Among the gait parameters, both age groups showed some indication of habituation over blocks, but these effects were not observed consistently. Notably, none of the block-wise results suggest strong effects of fatigue. Given the modest block-wise effects for single-task conditions, Blocks A and B for each condition were aggregated for all subsequent analyses.

Next, two-way ANOVAs, were conducted to examine differences in counterbalancing orders in listening performance and gait parameters for each age group (see Appendix D for counterbalance orders). For each dependent variable, listening conditions (within-subject factor) and block order (between-subject factor) were examined individually for each age group. For listening accuracy, there was no significant effect of counterbalance order in either age group. Among the gait parameters, there was a significant interaction of cognitive demands and counterbalance order in peak head pitch in younger adults, $F(6, 18) = 3.19$, $p = .026$, $\eta^2 = 0.36$. However, post-hoc contrasts revealed no significant differences between counterbalance orders for each cognitive demand in peak head pitch ($p > .05$). The lack of significant contrasts might be due to the smaller number of participants who completed certain counterbalance orders. Altogether, the order of counterbalancing did not influence listening performance or affect gait behaviour, thus all orders were pooled in subsequent analyses.

Lastly, independent samples *t*-tests were performed on the listening and kinematic data across the five different ratios used in the uncertain location probability conditions. These analyses revealed no significant differences ($p > .05$). Thus, all uncertain location trials were examined collectively as the ≤75% probability condition in subsequent analyses.

Listening Performance

Figure 2 illustrates word recognition accuracy across all listening conditions for each age group. The analyses revealed a significant main effect of task-type, $F(1, 27) = 28.85$, $p < .001$, $\eta^2 = 0.06$, in which listening performance in the dual-task condition was poorer ($M = 0.42$, $SD = 0.02$) than on single-task conditions ($M = 0.53$, $SD = 0.03$). A significant main effect of location certainty was also found, $F(1, 27) = 72.81$, $p < .001$, $\eta^2 = 0.18$, such that listening performance was poorer when the location of the target callsign was variable (≤75%; $M = 0.39$, $SD = 0.03$) than when the location was fixed (100%; $M = 0.56$, $SD = 0.02$). In addition, a significant main effect of age group was found, $F(1, 27) = 16.64$, $p < .001$, $\eta^2 = 0.24$, wherein older adults performed worse ($M = 0.37$, $SD = 0.03$) compared to younger adults ($M = 0.58$, $SD = 0.03$) across all listening conditions. A significant interaction was found for task-type and location certainty, $F(1, 27) = 8.21$, $p = .008$, $\eta^2 = 0.02$, wherein listening performance was worse in single-task conditions when the target callsign location was variable ($M = 0.42$, $SD = 0.03$) than fixed ($M = 0.63$, $SD = 0.03$), which was similar in dual-task conditions but with poorer listening accuracy when the target callsign location was variable ($M = 0.48$, $SD = 0.03$) compared to fixed ($M = 0.36$, $SD = 0.02$). No significant interaction was found for age group and location certainty, $F(1, 27) = 3.08$, $p = .091$, $\eta^2 = 0.01$, or between age group and task-type, $F(1, 27) = 3.17$, $p = .086$, $\eta^2 = 0.01$. However, there was a significant 3-way interaction between age group, task-type, and location probability, $F(1, 27) = 4.82$, $p = .037$, $\eta^2 = 0.01$. To further examine the interaction term between age group, task-type, and location probability, a 2 (task-type: single- vs. dual-task) X 2 (location certainty: 100% vs. ≤75%) ANOVA was performed separately for younger and older adults. For younger adults, the analyses showed a significant main effect of task-type, $F(1, 16) = 7.64$, $p = .014$, $\eta^2 = 0.07$, where listening performance was better under single-task ($M =$

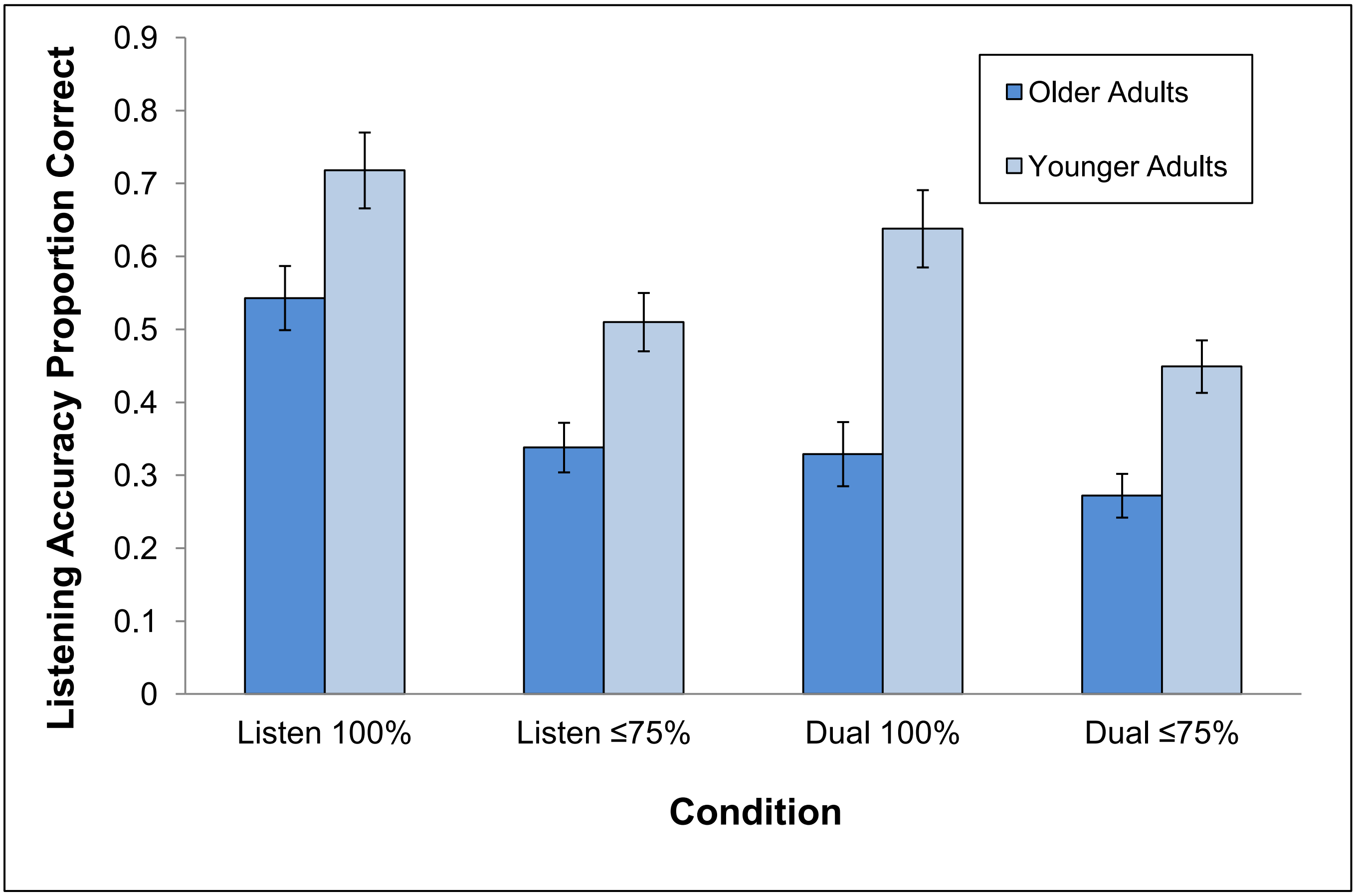


Figure 2. Mean word recognition accuracy (proportion of correct responses) as a function of task-type, location certainty, and age group. The error bars represent one standard error of the mean.

0.61, *SD* = 0.03) than dual-task conditions (*M* = 0.54, *SD* = 0.03). A significant main effect of location certainty was also found, *F*(1, 16) = 58.46, *p* < .001, η^2 = 0.55, such that listening performance was better when the location of the target callsign was fixed (*M* = 0.68, *SD* = 0.04) than when it was variable (*M* = 0.48, *SD* = 0.03). However, there was no significant interaction between task-type and difficulty, *F*(1, 16) = 0.28, *p* = .607, η^2 = 0.00. Similarly in the older adults, there was a significant main effect of task-type, *F*(1, 11) = 22.46, *p* = .001, η^2 = 0.30, wherein listening performance was better under single-task conditions (*M* = 0.44, *SD* = 0.03) than dual-task conditions (*M* = 0.30, *SD* = 0.03). As well, a significant main effect of location certainty was found, *F*(1, 11) = 22.69, *p* = .001, η^2 = 0.26, in which listening performance was worse when the target location was less predictable (*M* = 0.31, *SD* = 0.02) than when location was fixed (*M* = 0.44, *SD* = 0.44, *SD* = 0.04). Importantly, a significant interaction between task-type and location certainty was found, *F*(1, 11) = 10.73, *p* = .007, η^2 = 0.08, such that listening performance was worst under dual-task ≤75% (*M* = 0.27, *SD* = 0.02), followed by dual-task 100% (*M* = 0.33, *SD* = 0.03), single-task ≤75% (*M* = 0.34, *SD* = 0.03), and best under single-task 100% conditions (*M* = 0.54, *SD* = 0.05).

To summarize, the main effect of age group, task-type, and location certainty were significant. Most relevant for the hypotheses, older adults performed more poorly on the listening task under dual-task conditions than the younger adults, particularly when the location of the target callsign was less predictable. A closer examination of this interaction revealed that both age groups were negatively affected by the requirement to perform two concurrent tasks, however older adults showed a stronger effect.

Walking Performance

Analyses regarding mean levels of the key gait parameters will first be reported, followed by results on the variability (i.e., stability) of these parameters. Note that for upper body gait parameters, higher values indicate larger rotation (degrees from zero calculated from an aligned, full body static position) which is considered maladaptive.

Mean Level Gait Parameters. The results on average head pitch (i.e., forward rotation) are plotted in Figure 3. A mixed factorial ANOVA revealed a significant main effect of cognitive demands, $F(1.20, 29.99) = 7.57$, $p = .007$, $\eta^2 = 0.03$. Polynomial contrasts revealed significant linear, $F(1, 25) = 9.04$, $p = .006$, $\eta^2 = 0.02$, and quadratic functions, $F(1, 25) = 4.90$, $p = 0.036$, $\eta^2 = 0.01$, wherein dual-task ≤75% probability showed less head pitch rotation (measured in degrees; $M = 4.17$, $SD = 1.45$), than dual-task 100% probability ($M = 4.25$, $SD = 1.38$) and single-task walking ($M = 7.49$, $SD = 1.58$). In addition, a significant main effect of age group was found, $F(1, 25) = 6.85$, $p = .015$, $\eta^2 = 0.18$, wherein younger adults showed less head pitch rotation ($M = 1.22$, $SD = 1.76$) than older adults ($M = 9.39$, $SD = 1.89$). A significant interaction of age group and cognitive demands was also found, $F(1.20, 29.99) = 8.05$, $p = .006$, $\eta^2 = 0.03$. To explore this interaction term, individual one-way ANOVAs using cognitive demands as within-subject factors were performed separately for younger and older adults. The only significant finding was a main effect of cognitive demands in older adults, $F(1.14, 12.57) = 12.62$, $p = .003$, $\eta^2 = 0.53$. Polynomial contrasts revealed significant linear, $F(1, 11) = 15.25$, $p = .002$, $\eta^2 = 0.45$, and quadratic functions for the main effect of walking condition in older adults, $F(1, 11) = 6.75$, $p = .025$, $\eta^2 = 0.09$. In sum, older adults had the greatest head pitch rotation under single-task walking that decreased under dual-task ≤75% and dual-task 100%, while younger adults showed minimal variation as a function of cognitive demands, but notably in the opposite direction: greatest head pitch rotation was found in dual-task 100%, followed by single-

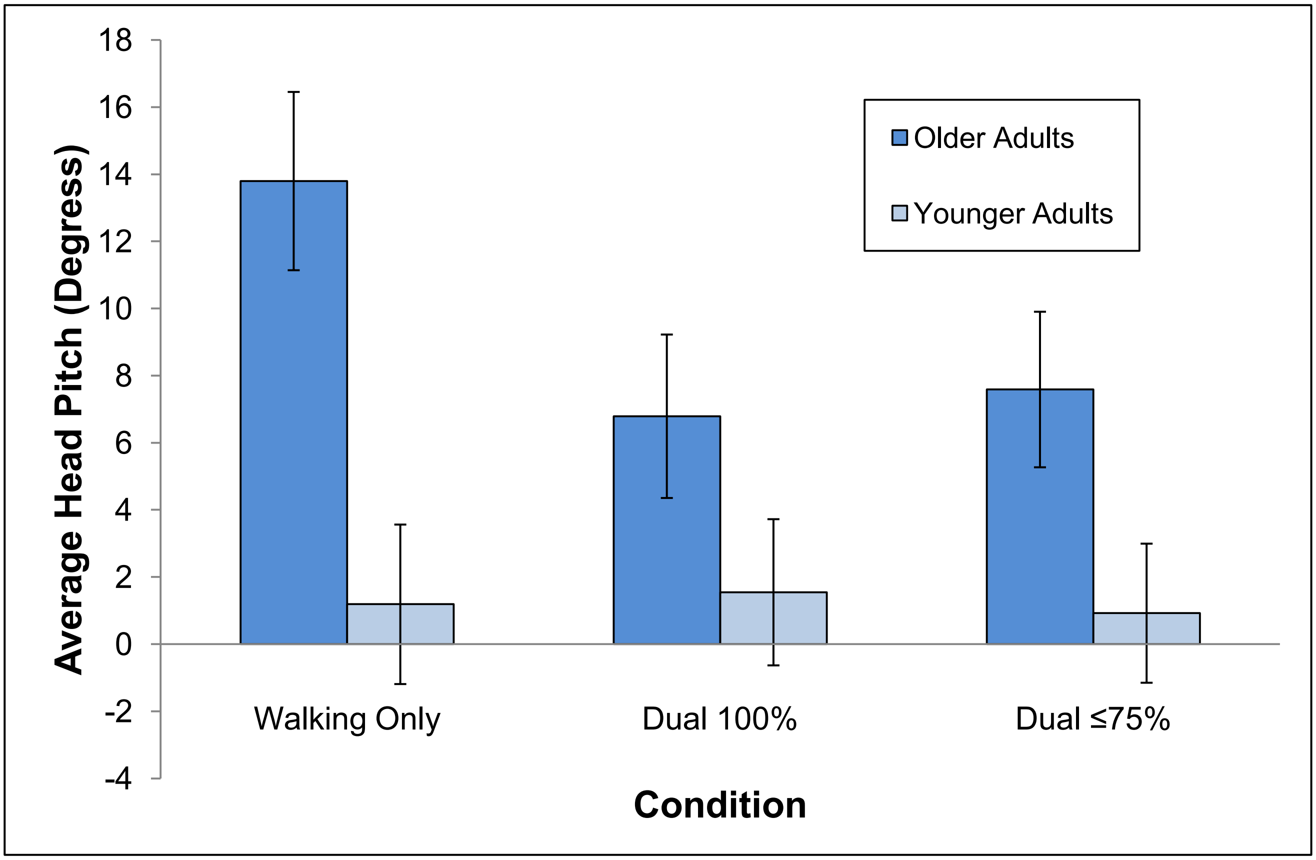


Figure 3. Average head pitch rotation (in degrees) across single-task walking and dual-task conditions between young and older adults. The error bars represent one standard error of the mean.

task walking and dual-task ≤75%.All other mean level parameters (upper or lower body) did not yield significant main effects or interactions. We next turn to analyses of gait variability.

Gait Variability. The variability of the gait parameters was considered, using coefficient of variation (CV). As previously described, larger CV values indicate less stable gait and are considered maladaptive. For the upper body parameters, a mixed factorial ANOVA revealed significant main effect of cognitive demand for trunk roll CV (i.e., rotation in degrees from left to right), $F(2, 50) = 57.66$, $p < .001$, $\eta^2 = 0.65$. Polynomial contrasts of cognitive demands revealed a significant linear, $F(1, 25) = 58.66$, $p < .001$, $\eta^2 = 0.34$, and quadratic function, $F(1, 25) = 56.58$, $p < .001$, $\eta^2 = 0.30$, such that there was lower variability in single-task walking ($M = -10.98$, $SD = 8.29$) which increased under dual-task ≤75% probability ($M = 2.58$, $SD = 2.56$) and dual-task 100% probability ($M = 6.74$, $SD = 4.48$).

Furthermore, a mixed factorial ANOVA revealed a significant main effect of cognitive demand in head roll CV (i.e., rotation in degrees from left to right), $F(2, 50) = 3.34$, $p = .043$, $\eta^2 = 0.01$. Polynomial contrasts revealed a significant quadratic function for cognitive demand, $F(1, 25) = 5.99$, $p = .022$, $\eta^2 = 0.01$, which was qualified by a significant quadratic function for the interaction of cognitive demand and age group, $F(1, 25) = 5.59$, $= .026$, $\eta^2 = 0.01$. A closer examination of this interaction revealed no significant polynomial contrasts in younger adults, however there was a significant quadratic function for cognitive demands in older adults, $F(1, 11) = 8.68$, $p = .013$, $\eta^2 = 0.29$. Specifically, older adults showed greatest variability in head roll under dual-task 100% ($M = 3.03$, $SD = 3.19$), followed by a decrease in variability in dual-task ≤75% ($M = 2.49$, $SD = 2.60$) and single-task walking ($M = 2.18$, $SD = 2.39$).

The lower body CV parameters reflect spatiotemporal inconsistency or instability. Given that the mean level analyses of the lower body parameters did not yield significant effects or interactions, we focus here on CV as a more sensitive index of gait patterning and regularity.

Stride time variability serves as a common measure of gait regularity and control. Previous work has shown that it is sensitive to cognitive load, correlated with executive functions, and predictive of falls. Since a mixed factorial ANOVA design did not yield significant effects, a MANOVA was conducted. There was a significant interaction of age group and cognitive demands for stride time variability (SD/M) was found, V = 0.22, $F(2, 26) = 3.69$, $p = .039$, $\eta^2 = 0.00$, see Figure 4. Pairwise comparisons only revealed a significant difference between single-task walking and dual-task ≤75% ($SE = 0.00$, $p = .039$) in older adults.

Similarly, variability of cadence did not yield significant effects using ANOVA. However, cognitive demands in each age group were observed in a MANOVA. The variability of cadence (i.e., number of steps per minute) showed a significant interaction of cognitive demands and age group, V = 0.22, $F(2, 26) = 3.72$, $p = .038$, $\eta^2 = 0.00$, see Figure 5. Polynomial contrasts revealed a significant quadratic function for the cognitive demands and age group interaction, $F(1, 27) = 6.52$, $p = .017$, $\eta^2 = 0.00$. In particular, older adults increased variability in cadence from single-task walking to dual-task ≤75% and dual-task 100%, whereas younger adults displayed lower variability in cadence in dual-task 100% that increased in single-task walking, followed by dual-task ≤75%. Pairwise comparisons revealed a significant difference between dual-task 100% and dual-task ≤75% ($SE = 0.01$, $p = .041$) in younger adults. No other significant contrasts were found.

Dual-Task Costs

DTCs were calculated as a derived difference score between baseline single-task

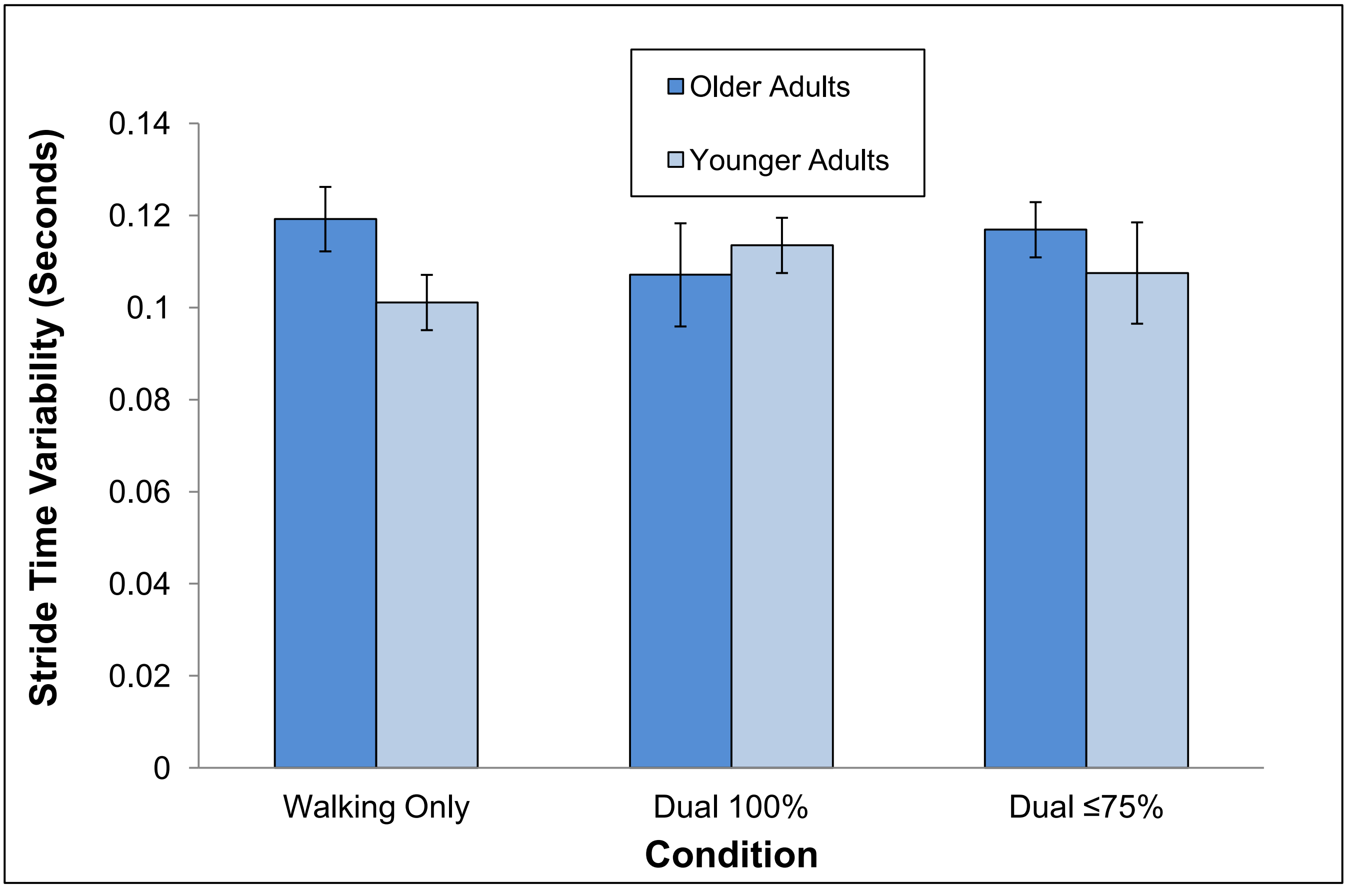


Figure 4. Stride time variability (in seconds) is displayed for single-task walking and dual-task conditions for younger and older adults. The error bars represent one standard error of the mean.

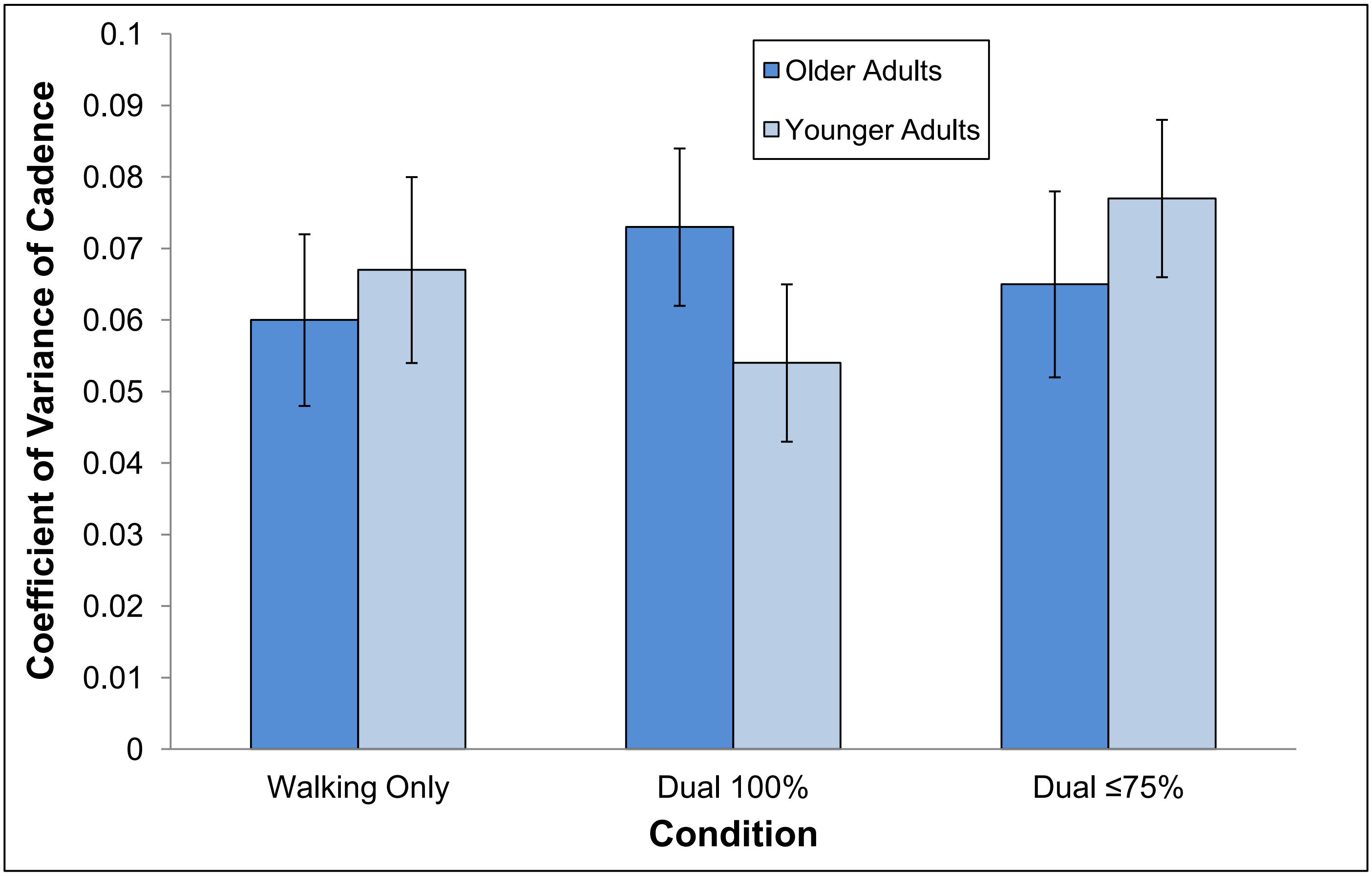


Figure 5. The coefficient of variation of cadence illustrated across single-task walking and dual-task conditions as a function of age group. The error bars represent one standard error of the mean.

performance and dual-task performance across listening and gait parameters. This is a more conservative estimate of the effects of cognitive load that corrects for individual differences in baseline single-task performance. In the listening task, higher DTCs represent a greater performance reduction due to concurrent walking. The mixed ANOVA analysis of DTCs in listening performance revealed a significant main effect of location certainty, $F(1, 27) = 8.21$, $p = .008$, $\eta^2 = 0.09$, wherein DTCs were greater in the 100% ($M = 0.14$, $SD = 0.16$) than the ≤75% condition ($M = 0.06$, $SD = 0.10$). This main effect was qualified by a significant interaction of age group and task, $F(1, 27) = 4.82$, $p = .037$, $\eta^2 = 0.05$. To explore this interaction, individual one-way ANOVAs for task were conducted for both age groups. The only significant finding was a main effect of task in older adults, $F(1, 11) = 10.73$, $p = .007$, such that older adults displayed larger DTCs in the 100% condition ($M = 0.21$, $SD = 0.04$) than the ≤75% condition ($M = 0.07$, $SD = 0.02$).

Turning to the gait parameters, DTCs for head and trunk parameters, as well as CV gait measures, were calculated as a derived difference score from dual-task to single-task performance, wherein high values signal maladaptive gait. The mixed ANOVA analyses revealed a significant main effect of age group in average head pitch, $F(1, 25) = 8.61$, $p = .007$, $\eta^2 = 0.25$, such that older adults exhibited smaller DTCs ($M = -6.61$, $SD = 1.37$) than younger adults ($M = 0.05$, $SD = 1.26$). A significant main effect of task in peak trunk roll was found, $F(1, 25) = 21.52$, $p < .001$, $\eta^2 = 0.24$, wherein there was larger DTCs for the ≤75% condition ($M = 3.40$, $SD = 3.31$) than the 100% condition ($M = 0.48$, $SD = 1.34$). In the same parameter, there was also a significant main effect of age group, $F(1, 25) = 5.72$, $p = .025$, $\eta^2 = 0.08$, that showed smaller DTCs in older adults ($M = 1.02$, $SD = 0.42$) than in younger adults ($M = 2.67$, $SD = 0.38$). In stride time variability DTCs, a significant main effect of age group was found, $F(1, 27)$

= 4.44, *p* = .045, η^2 = 0.00, indicating slightly smaller DTCs for older adults (*M* = -0.01, *SD* = 0.00) compared to younger adults (*M* = 0.01, *SD* = 0.00). Overall, the DTC analyses indicate that the DTCs were greater for older adults than younger adults in the cognitive domain, but the opposite was true in the walking domain.

Attentional Allocation between Tasks

To better understand the dynamics of attentional allocation between listening and walking tasks during dual-task conditions, zero-order correlations were performed using pairs of dual-task measures (e.g., listening at 100% paired with walking at 100%). In older adults, a significant negative correlation was found between listening performance and average head pitch in dual-task 100% (*r*(11) = -.80, *p* = .002, see Figure 6a). In addition, significant negative correlations were obtained between listening performance and average head pitch in dual-task ≤75% (*r*(11) = -.74, *p* = .006, see Figure 6b). In younger adults, there was a significant negative correlation between listening performance and peak head roll under dual-task ≤75% (*r*(14) = -.62, *p* = .014, see Figure 7). Across all of these correlations, the negative associations indicate that good listening performance was associated with more upright head alignment.

Background Clinical Measures

Table 1 reports the mean and standard deviation for each background clinical measure of cognition and sensory function for younger and older adults, as well as significant age group differences.

In order to investigate the association between the key experimental measures with the background measures of cognition, sensory, and physical functioning, Pearson *r* correlations were performed for each age group separately. Table 2 lists the significant correlations for

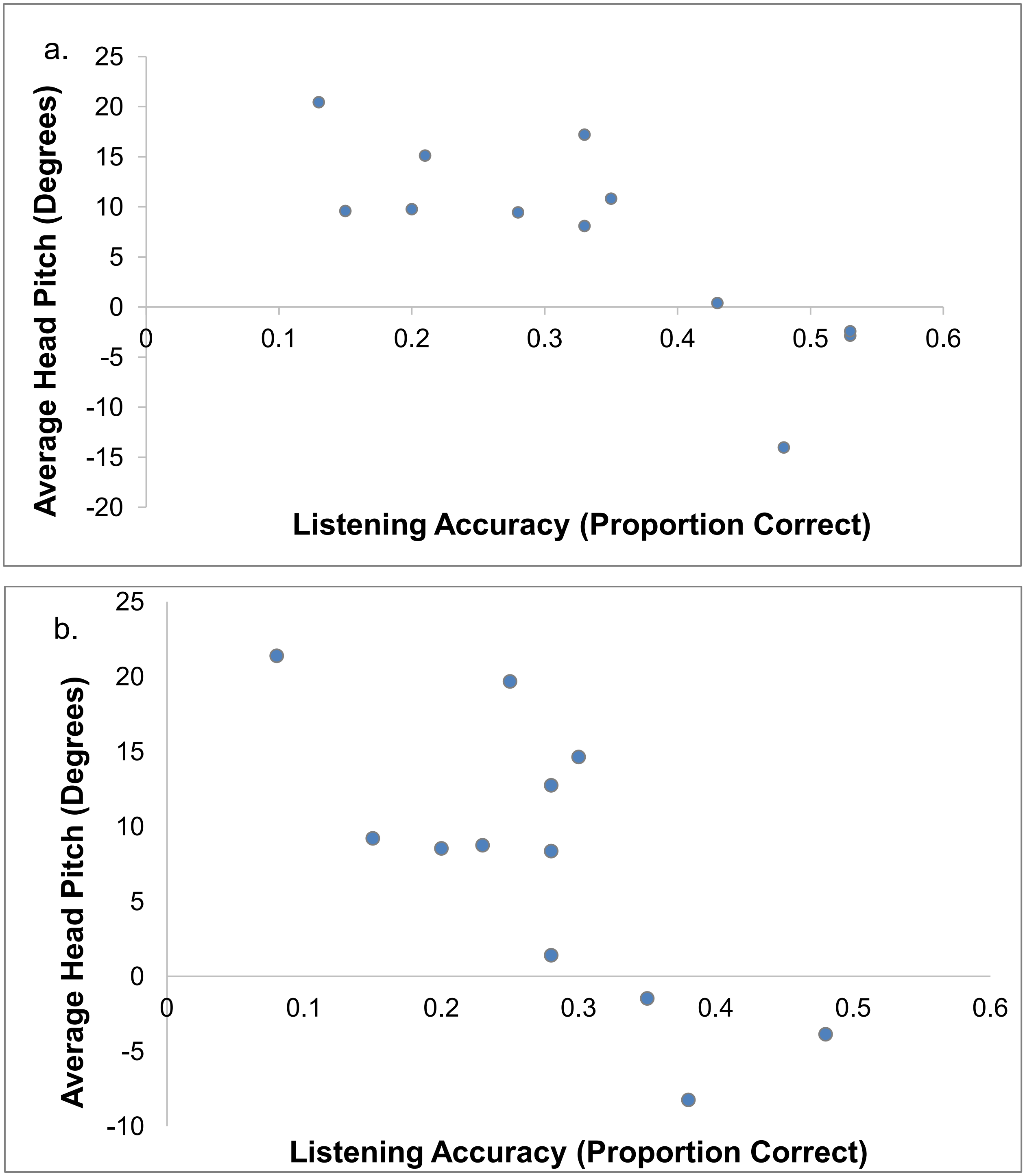


Figure 6. (a) Zero-order correlation is displayed for dual-task 100% probability listening accuracy and dual-task 100% probability average head pitch in older adults ($r(11) = -.80$, $p = .002$). (b) Zero-order correlation is displayed for dual-task ≤75% probability listening accuracy and dual-task ≤75% probability average head pitch in older adults ($r(11) = -.74$, $p = .006$).

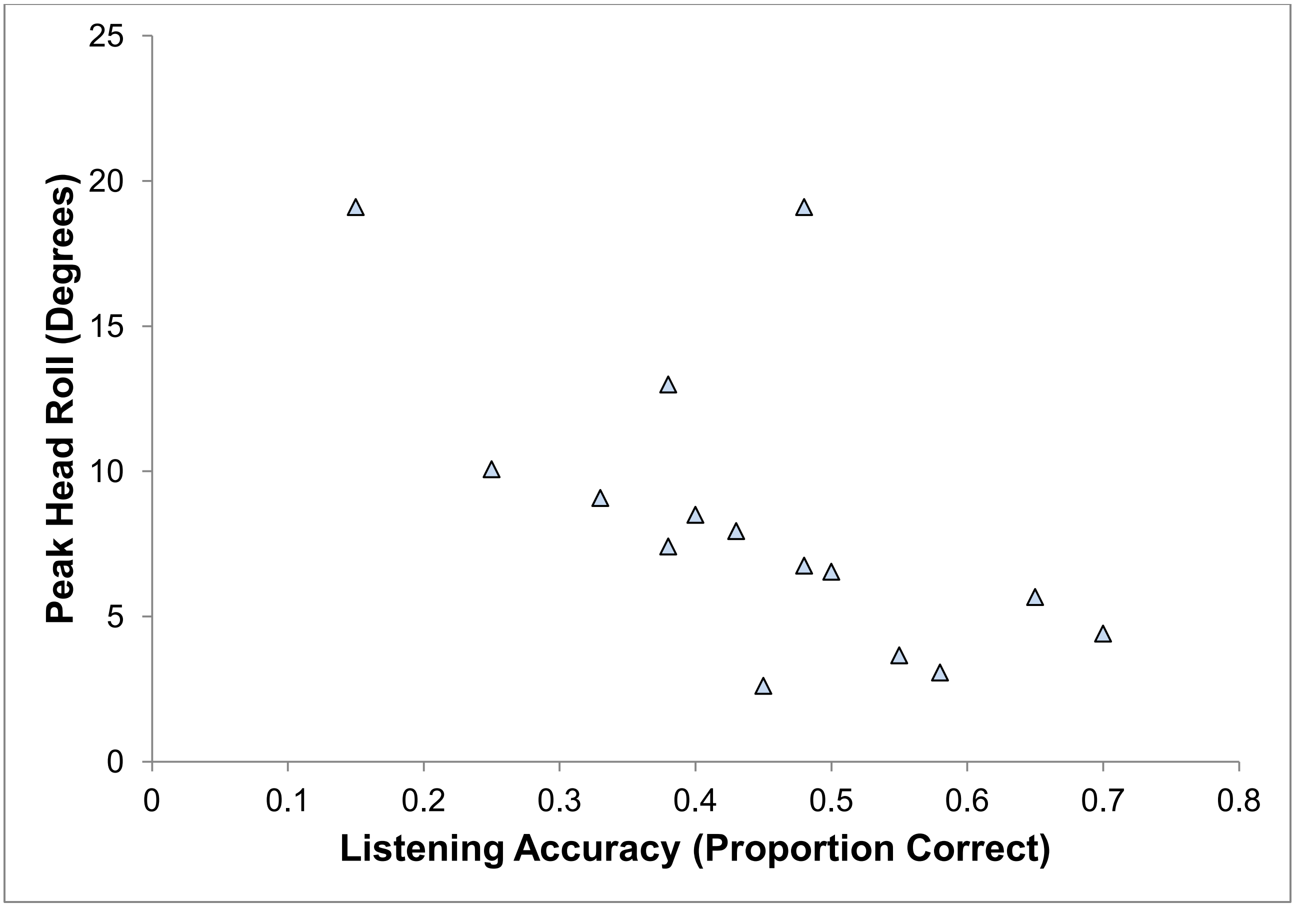


Figure 7. Zero-order correlation is displayed for dual-task ≤75% probability listening accuracy (measured as proportion of correct responses) and peak head roll (measured in degrees) for younger adults (*r*(14) = -.62, *p* = .014).

Table 1

Mean and Standard Deviation for Neuropsychological, Sensory, and Motor Tests for Each Age Group

Variable	Older Adults		Younger Adults				
	M	*SD*	*M*	*SD*	*t*	df	*p*
PTA (Better Ear) dB/HL	8.82	4.58	3.23	2.97	-3.99	27	.000
WIN (Better Ear) dB/HL	11.20	4.91	7.69	2.90	-2.22	16.38	.041
MoCA	30.17	5.13	[a]-	-	-	-	-
LNS	10.08	1.62	12.35	1.90	3.36	27	.002
DSC	66.08	10.08	94.24	12.56	6.43	27	.000
Stroop Test	0.67	0.25	0.64	0.21	-0.35	27	.728
DKEFS – TMT	36.21	36.42	27.84	15.25	-0.75	13.75	.466
ABC	96.14	4.98	96.05	3.76	-0.60	27	.954
DGI	23.83	0.39	[a]-	-	-	-	-
TUG Test	8.08	2.27	[a]-	-	-	-	-

Note. PTA = Pure Tone Average threshold. WIN = Words-in-Noise. MoCA = Montreal Cognitive Assessment, total score out of 30. LNS = Letter Number Sequencing, total number of correct responses out of 30. DSC = Digit Symbol Coding, total number of correct responses in 2 minutes. Stroop Test is measured as the difference score of the number of correct responses by completion time (in seconds) between the control and experimental condition. DKEFS - TMT = Delis Kaplan Executive Function System - Trail Making Test, total score of condition 4 subtracted by the average of condition 2 and 3. ABC = Activities-Specific Balance Confidence Scale, total score out of 100. DGI = Dynamic Gait Index, total score out of 24. TUG = Timed Up & Go, measured as completion time (in seconds). [a]Tests were only performed on older adults.

Table 2

Correlations between background measures and listening and gait performance by age group

	Younger Adults								
	Executive Function Measures					Sensory Measures			
Performance variable	DSC	DKEFS	LNS	Stroop	MoCA	TUG	ABC	DGI	WIN
Listening task									
DT100%	-.71**	-	-	-	-	-	-	-	-
Upper body gait measures									
AVG trunk roll-DT75%	-	-	-	-	-	-	-	-	.52*
PK trunk roll-DT75%	-	-	-	-	-	-	-.52*	-	-
CV PK head pitch-STW	-	-	-	-	-	-	-.55*	-	-
CV PK head pitch-DT100%	-	-	-	-	-	-	.52*	-	-
CV PK head roll-STW	-	-	-.56*	-	-	-	-	-	-
CV trunk roll-STW	-.53*	-	-	-	-	-	-	-	-
CV PK trunk roll- STW	-	-	-	-	-	-	.56*	-	-
Lower body gait measures									
AVG step width-STW	-	.61**	-.52*	-	-	-	-.50*	-	-
AVG step width-DT100%	-	.60*	-.51*	-	-	-	-	-	-
AVG step width-DT75%	-	.69**	-.49*	-	-	-	-	-	-
AVG stride length-STW	-	-	-	-.58*	-	-	-	-	-
AVG stride length-DT100%	-	-.53*	-	-.60*	-	-	-	-	-
AVG stride length-DT75%	-	-	-	-.58*	-	-	-	-	-
Cadence -STW	-	-	-	.52*	-	-	-	-	-
AVG stride time-STW	-	-	-	-.53*	-	-	-	-	-
AVG stride time-DT100%	-	-.53*	-	-.63**	-	-	-	-	-
AVG stride time-DT75%	-	-	-	-.55*	-	-	-	-	-
CV step width-DT75%	-	.50*	-	-	-	-	-	-	-
CV stride length-STW	-.51*	-	-	-	-	-	-	-	-
CV stride length-DT100%	-.63**	-	-	-	-	-	-	-	-
CV stride length-DT75%	-.52*	-	-	-	-	-	-	-	-

	Older Adults								
	Executive Function Measures					Sensory Measures			
Performance variable	DSC	DKEFS	LNS	Stroop	MoCA	TUG	ABC	DGI	WIN
Listening task									
ST100%	-	-.61*	-	-	-	-	-	-	-
ST75%	-	-	-	-	-	.77*	-	-	-
DT100%	-	-	-	-	.59*	-	-	-	-
Upper body gait measures									
AVG head pitch-DT75%	-	-	-	-	-	-	-	-	-.61*
AVG head pitch-DT100%	-	-	-	-	-	-	-	-	-.73**
PK head pitch-DT75%	-	.71*	-.65*	-	-	-	-	-	-
PK head roll-STW	-	-.73**	-	-	-	.77*	-	-	-
PK head roll-DT100%	-	.64*	-	-	-	-	-	-	-
PK head roll-DT75%	-	-	-	-	-	.81*	-	-	-
PK trunk roll-DT100%	-	-	-	-	-	-	-.68*	-	-
CV PK head pitch-STW	-	.63*	-	-	-	-	-	-	-
CV PK head pitch-DT75%	-	-	-	-.59*	-	-	-	-	-
CV PK head roll-STW	-.64*	-	-	-	-	-	-	-	-
CV trunk roll-DT100%	-	-	-	-	-	-	-.69*	-	-
CV PK trunk roll-STW	-	-	-	-.65*	-	-	-	-	-
CV PK trunk roll-DT100%	-	-	-	-	-	-	-.68*	-	-
CV PK trunk pitch-DT100%	-	-	-	-.78**	-	-	-	-	-
CV PK trunk pitch-DT75	-	-	.61*	-	-	-	-	-	-
Lower body gait measures									
AVG stride length-DT75%	-	-	-	-	-	-	-	.58*	-
Cadence-DT75%	.58*	-	-	-	-	-	-	-	-
CV cadence-DT100%	-	-	-	-	-	.83*	-	-	-
CV stride time-DT100%	-	-	-	-	-	.93**	-	-	-
CV stride time-DT75%	-	-	-	-	-	.92**	-	-	-

Note. Pearson r correlation coefficients are presented. ST100% = Single-task listening 100% probability. ST75% = Single-task listening ≤75% probability. STW = Single-task walking. DT100% = Dual-task 100% probability. AVG = average. PK = peak. CV = Coefficient of Variation (standard deviation / mean). DSC = Digit Symbol Coding. DKEFS = Delis Kaplan Executive Function Systems – Trail Making Test. MoCA = Montreal Cognitive Assessment. TUG = Timed Up & Go Test. ABC = Activities-Specific Balance Confidence Scale. DGI = Dynamic Gait Index. WIN = Words-in-Noise Test. *$p < .05$, **$p < .01$.

younger and older adults. The significant correlations found in the young data were primarily limited to the lower limb gait parameters. Processing speed (DSC) was associated with more regular stride length across all cognitive demand conditions. Better executive functioning (TMT, LNS, Stroop) was associated with narrower step widths, and longer steps. In the older data, executive functioning was largely associated with head and trunk alignment and not with the spatiotemporal gait parameters, although the overall correlational patterns were not as consistent as in the young adults. Notably, these relationships were negative, suggesting that older adults with poorer executive functioning may have been prioritizing alignment more so than their peers with well preserved executive control. The few significant correlations between neuropsychological measures (TMT, MoCA) and listening performance were positive, suggesting that better cognitive status was associated with better listening performance. Unlike the younger adults, older adults also showed relationships between the gait parameters and the clinical measures of mobility (TUG) and balance confidence (ABC), such that those with slower TUG completion times showed greater gait variability and head pitch, while those with lower balance confidence showed worse trunk alignment and variability of trunk alignment.

Discussion

The purpose of this study was to investigate age-related increases in competition for cognitive resources between complex auditory function and walking in a dual-task paradigm. Cognitive competition was evaluated as a theoretical explanation for the epidemiological findings linking age-related hearing loss and mobility decline. To our best knowledge, this is the first study to experimentally examine this association. Auditory processes were examined using a real spatial separation multitalker design with varying target location certainty (Singh et al., 2008) to mimic everyday listening and to simulate group conversation, which is a challenge often identified by older adults. To further increase the ecological validity of the experiment, listening and walking were studied in a VR simulation of a street crossing, which is challenging for older adults and has important safety implications. It was hypothesized that older adults would exhibit greater dual-task performance costs compared to younger adults because of competition for scarce cognitive resources. These dual-task costs were hypothesized to increase under more challenging listening conditions (i.e., variable target location). It was also hypothesized that older adults would allocate more cognitive resources to favour safe walking over accurate listening, whereas younger adults would more flexibly allocate resources between walking and listening performance.

Listening Performance

With respect to listening performance, the results of this study are clear. As predicted, dual-task listening performance was worse than single-task performance. As well, listening performance was better when the location of the target callsign was certain. As anticipated, older adults exhibited poorer word recognition accuracy across all conditions when compared with younger adults, particularly under dual-task conditions. As hypothesized, older adults were more negatively affected when the location of a target became less probable than fixed compared to younger adults. This last finding is in disagreement with work by Singh and colleagues (2008), who found equivalent effects of location probability in both age groups. However, the discrepancy can be explained by methodological differences between studies: Singh and colleagues tested their participants under single-task seated listening conditions in an anechoic chamber, whereas in the current study, participants were standing and walking during single- and dual-task performance. Furthermore, both age groups were affected by dual-task conditions, however older adults were disproportionately affected by these manipulations, in agreement with previous studies (Li et al., 2001; Li, Abbud, Fraser, & DeMont, 2012; Lindenberger et al., 2000; Maylor & Wing, 1996). Therefore, older listeners were challenged by the additional cognitive demands that were introduced by having to attend to, follow, and segregate multiple speech streams (Murphy et al., 2006).

The findings of lower word recognition performance with uncertain target location (i.e., the main effect of location certainty) can be explained in several ways. One explanation is that when the location of the target was uncertain, binaural cues were less available to the listener when they attended to multiple spatial locations, whereas under fixed location conditions, the masking of the target callsign is minimal and the sound sources can be successfully segregated (Kidd, Arbogast, Mason, & Gallun, 2005). A second possibility is that in the ≤75% condition, listeners strategically focused on the most likely spatial location (i.e., the center spatial location) for each block and then switched attention to the less likely spatial locations when necessary. If attention is initially directed to the wrong spatial location, performance will suffer because it diminishes the ability to follow the correct speech stream (Kidd et al., 2005). A third possibility is that as the location certainty decreased, the listener widened their attentional range to more of the possible locations. Possibly, listeners may have used a combination of attention switching and broadening their attentional range (Singh et al., 2008).

There are multiple mechanisms that might underpin the observed age main effect of word recognition performance. Firstly, older listeners might be unable to take advantage of the auditory cues available from spatially separated talkers. It is found that the ability to spatially separate a target from maskers aids in word recognition performance (Freyman, Balakrishnan, & Helfer, 2001). Age-related decline in the ability to segregate the target from a masker may lead to inefficient cognitive processing of speech and explain why older listeners are more challenged than younger listeners on the listening task (Murphy et al., 2006). Another possibility is that older adults could be in the early stages of presbycusis (Schneider, 1997). Even though both age groups showed normal hearing levels, older adults had on average higher pure tone thresholds across all tested hearing frequencies, particularly in higher frequencies. Individuals with high frequency hearing loss do not benefit from the spatial separation of a target from noise due to improvement in SNR in higher frequencies declines (Bronkhorst & Plomp, 1989). Alternatively, older listeners might not be able to benefit from binaural interaction (Bronkhorst & Plomp, 1988). Age-related differences in processing binaural cues might explain older listeners' inability to use these cues to facilitate sound localization and reallocate spatial attention (Singh et al., 2008).

Individual Differences in Listening Performance. The correlational analyses further elucidate the cognitive underpinnings of word recognition performance. Consideration of the neuropsychological and motor tests revealed dissimilar patterns in each age group. For younger adults, processing speed was negatively associated with listening performance, surprisingly. The pattern is clearer in the older adults' correlations, wherein higher global cognitive functioning (i.e., MoCA scores) was associated with better word recognition performance in dual-task conditions. Furthermore, better executive function and mental flexibility (i.e., DKEFS - TMT) were linked with higher word recognition performance under single-task conditions. Interestingly, low mobility (slower completion times on the TUG test) was linked with higher word recognition performance in older adults. This pattern contradicts past research that showed slower walking speed was linked with poorer executive functioning (McGough et al., 2011), and underscores the need for more detailed examination of this link in future studies. Overall, these correlational analyses revealed that higher cognitive functioning and flexible thinking in older adults was associated with better listening performance. Possibly, those older adults with efficient cognitive control could discern the target sentence more easily, and had greater overall capacity to distribute between the listening and walking tasks under dual-task conditions.

Walking Performance

Average Gait Measures and Gait Variability. The present findings on walking performance join others in supporting the notion that in old age, walking calls upon cognitive function (Hausdorff et al., 2005; Holtzer, Verghese, Xue, & Lipton, 2006; Lindenberger et al., 2000). The gait findings revealed novel insights into the link between auditory challenge and walking under dual-task conditions. Under increased cognitive load, older adults showed a more upright head position and became more regular in their stride time. However, older adults also displayed increased variability in cadence and head rotation from side-to-side under dual-task conditions. On the other hand, younger adults displayed an opposite pattern of gait execution wherein there was greater variability in stride time under dual-task conditions.

Variability in gait has been described as a more accurate predictor of falls and mobility decline than absolute gait measures, such as mean velocity (Hausdorff et al., 2001; Maki et al., 1997). Prior studies have proposed that stride time variability is associated with cognitive function in that executive functions are needed to regulate stable walking rhythm (Hausdorff et al., 2005). It is also shown that stride time variability increases during dual-tasking among individuals with impaired executive functions (Hausdorff, Balash, Giladi, 2003; Sheridan, Solomont, Kowall, & Hausdorff, 2003). Although a curvilinear pattern in stride time variability and was found, the reduced variation under dual-task conditions suggests recruitment of cognitive resources to aid walking in old age. Conversely, variability in cadence increased under dual-task conditions in older adults, which suggests that not all aspects of gait were improved despite postural prioritization. Overall, the evidence indicates that cognitive control of walking increases in old age, while in young adulthood walking may perhaps be more independently organized by the motor system (Lövdén, Schaefer, Pohlmeyer, & Lindenberger, 2008).

Altogether, these gait findings suggest that older adults were allocating attentional resources toward walking to maintain safe and stable gait, whilst younger adults appeared to divide their attention more evenly between listening and walking, as evidenced by their increased gait variability under dual-task conditions. Hence, the gait findings corroborate the present interpretation of the listening accuracy findings in terms of attentional allocation and postural prioritization.

Dual-Task Costs

The DTC analyses were conducted to further examine the relative allocation of cognitive resources between the two domains of functioning. It was predicted that older adults would exhibit larger DTCs in the cognitive listening domain due to overall decline in cognitive capacity. As well, if older adults prioritized walking regularity over listening there would be smaller DTCs in gait performance expected. Indeed, the current findings supported the hypothesis that older adults should exhibit larger DTCs on the cognitive listening task but smaller DTCs in gait behaviour compared to their younger counterparts. In regards to upper body gait parameters (average head pitch and peak trunk roll), older adults displayed smaller DTCs indicative of improved upper body alignment and reduced variation in stride time under dual-task conditions, unlike the younger adults. When considering lower body gait parameters, older adults showed slightly smaller DTCs in stride time variability than the younger adults. These findings are inconsistent with the maladaptive gait behaviour in older adults reported in past studies (Chen et al., 1996; Lindenberger et al., 2000; Mulder, Berndt, Pauwels, & Nienhuis, 1993), wherein older adults demonstrated larger costs because they have fewer attentional resources to distribute among multiple tasks (Craik & Byrd, 1982). This contradiction could be explained due to the complex nature of the listening task and the dynamic street crossing utilized in this study. The present design likely created increased cognitive challenge and sensory demands, and as a result, increased the need for postural prioritization. That DTCs were more apparent in cognitive listening performance than motor performance in older adults, is consistent with age-comparative research on postural prioritization (Li et al., 2012). Also in line with previous work (Coppin et al., 2006; Springer et al., 2006), dual-task effects are related to cognitive function, specifically attentional capacity and executive functions. Hence, changes in gait among older adults may call upon more cognitive capacity, and in turn, result in more cognitive listening performance costs.

In addition to the global pattern of postural prioritization, older adults were further sensitized to the manipulation of location certainty. Gait performance consistently revealed a curvilinear pattern in the older adults. In particular, in several gait parameters, (e.g., trunk and head roll CV), older adults showed the greatest variability under 100% dual-task conditions, and similar performance in single-task walking and 75% dual-task conditions. These results contradict the simple notion that balance and gait should be impaired with higher cognitive demands (Huxhold et al., 2006; Lindenberger et al., 2000). Instead, the current findings suggest that concurrent walking and listening produce different trade-offs at different cognitive levels that produce linear or quadratic patterns (Lövdén et al., 2008; Yerkes & Dodson, 1908). That is, under dual-task 100% conditions, older adults might be attempting to allocate attentional resources more evenly between walking and listening. However, under dual-task ≤75% conditions older adults might have reached a functional limit where they were unable to divide resources between both domains, and in turn, focus their cognitive resources toward walking at a cost to listening performance. This idea is supported by the similar performance in dual-task ≤75% and single-task walking conditions. Thus, under conditions of high cognitive load older adults may allocate more resources toward gait, leaving fewer available resources toward the secondary cognitive auditory task (Kahneman, 1973, also see Li et al., 2012).

Attentional Allocation between Listening and Walking

Taken together, our findings showed distinct age-related differences in the use of cognitive capacity between tasks of listening and walking under divided attention. As noted by Hausdorff and colleagues (2005), age-normative changes in motor control and sensory feedback might lead to diminished automaticity of walking and requires cognitive resources to effectively integrate sensory information to maintain balance during gait. In our cohort, we tested healthy, hearing-intact older adults; however it is known that even among this group there are expected changes to auditory processing (Schneider & Pichora-Fuller, 2000). As a result, multi-tasking likely led our older adults to recruit executive functions in response to increased auditory and cognitive challenges, leading to worsened listening performance and an asymmetrical allocation of attentional resources to protect walking. As predicted, older adults exhibited more cautious walking under the most cognitively demanding conditions (≤75%), whereas younger adults typically did not favour their gait, but distributed their attention more evenly between the two tasks.

The expected pattern of postural prioritization (Shumway-Cook et al., 1997b) in older adults is further supported by the listening performance data, wherein older adults performed worse than the younger adults overall. Specifically, older listeners were disproportionately affected by the dual-task and location certainty manipulations in comparison to younger adults. It is important to note that no explicit task prioritization instructions were given to participants. Accordingly, from an ecological standpoint, older adults prioritized walking because it minimized the risk of falls and imbalance and maximized avoidance of hazards (Li et al., 2005; Yogev-Seligmann, Hausdorff, & Giladi, 2012). Our findings also align with the assumptions of the SOC model of lifespan development (Baltes & Baltes, 1990), in showing that older adults with reduced cognitive capacity appear to selectively maintain and prioritize the most important goal (i.e., safe walking) at a cost to other competing goals (i.e., listening).

Individual Differences in Gait Performance. Focusing on the neuropsychological evidence, older adults showed several significant correlations with upper body gait parameters. Namely, better executive functioning (DKEFS, LNS) was linked with better posture in the head and trunk. Furthermore, better mobility function (faster TUG completion time) and higher balance confidence (ABC) were associated with better alignment in the head and trunk. These findings underscore the idea that increased deviation of the head position from an upright alignment may increase falls risk. In contrast, younger adults showed fewer significant correlations between neuropsychological measures and upper body gait parameters. In particular, better executive function (LNS) and faster processing speed (DSC) were associated with better alignment in the head and trunk, while balance confidence (ABC) was not consistently linked with superior gait performance.

In comparison to younger adults, older adults showed fewer significant correlations between the spatiotemporal gait parameters and the neuropsychological tests. Surprisingly, slower processing speed (DSC) was linked with higher cadence in older adults, in contrast to previous work by Holtzer and colleagues (2006) that showed a positive relationship. More predictably, longer TUG completion time was strongly associated with increased variability in cadence and stride time in the older adults. Longer TUG completion times have been associated with greater balance impairment and risk of falling in older adults (Shumway-Cook, Brauer, & Woollacott, 2000). In contrast to the sparse associations between EFs and spatiotemporal gait parameters, the younger adults showed very consistent relationships across multiple conditions and measures: Better processing speed (DSC) and executive function (DKEFS, LNS, Stroop) were associated with greater stride length, cadence, as well as reduced step width, stride length variability, indicating faster and more consistent gait (Atkinson et al., 2007; Ble et al., 2007; Holtzer et al., 2006; Holtzer, Wang, & Verghese, 2012; Persad et al., 1995).

Aging and Upper Body Postural Control

An important feature of the current study was the inclusion of upper-body analyses. This is a particularly important consideration given that the concurrent task involved spatial listening. Among the upper body parameters examined, our most noteworthy finding is the reduced head pitch rotation under dual-task conditions in older adults. The head is sometimes treated as an extension of the trunk or even disregarded in gait analyses, however the head contains two critical perceptual systems, vestibular and visual (Hirasaki, Kubo, Nozawa, Matano, &

Matsunaga, 1993). In order to have postural control during locomotion, the correct angle of the head must be maintained relative to gravity (Hirasaki et al., 1993). The regulation of head movement also influences the coordination of all body segments required for locomotion (Hicheur & Berthoz, 2005). Elderly persons with vestibular deficits have been shown to have large head pitch angles which can suggest that the vestibular system influences the position of the head (Hirasaki et al., 1993). Furthermore, it is proposed that as sensitivity of the semicircular canals (part of the inner ear) increases, animals will align their head during locomotion (Hirasaki et al., 1993). It is important to note that hearing and vestibular organs share anatomical structures, blood circulation, and nervous system components (Viljanen et al., 2009a).

In relation to the current findings on head pitch, when faced with complex task demands, such as listening to a target sentence amongst multiple talkers, the upper body is likely to change. In particular, older adults will straighten their head to a more upright position as a potential mechanism to maintain safe walking and manage increased cognitive load. Thus, the presently reported pattern of head pitch findings in older adults might indicate an adaptation to dual-task demands. Our correlational results between listening and head pitch extend these ideas. Older adults who showed a more upright head position under dual-task conditions performed better on the listening task. On the other hand, older adults who were less able to regulate head stability during walking performed worse on the listening task. These results are in disagreement with the common belief that leaning forward will improve listening. One plausible explanation is that older adults who are better at maintaining stable posture during locomotion are able to safely devote more attention towards listening performance. Therefore, postural control of the upper body might be a critical component in understanding speech in multiple speaker situations, a factor that has been largely overlooked in past studies. These findings complement studies with clinical populations, such as osteoporotic women with kyphosis (i.e., disfigurement of the spine) who are more susceptible to gait disorders and falls compared to healthy controls (Sinaki, Brey, Hughes, Larson, & Kaufman, 2005). These risks are increased in osteoporotic patients with exaggerated anterior curvature of the thoracic spine known as hyperkyphosis or dowager's hump (Kado, Huang, Nguyen, Barrett-Connor, & Greendale, 2007).

Limitations and Future Directions

The findings of this study should be interpreted with caution due to several limitations. Although our study attempted to capture elements of a natural, multi-talker environment, there were notable differences in the present task compared to real conversations. For example, the sentences were not semantically rich or syntactically variable, and were more fragmented than natural speech. It is known that older adults use linguistic knowledge (i.e., top-down processes) to compensate for perceptual decline, thus older listeners were likely unable to use the full extent of their cognitive and linguistic knowledge (Wingfield & Tun, 2001). Therefore, it would be of interest in future studies to move beyond simple word recognition towards a more naturalistic speech understanding task in a similar dual-task paradigm.

Another concern involves the sample of participants used, which consisted of healthy and fairly fit older adults who may not be representative of the general population. As well, many candidates were initially screened but not invited to participate in the experimental session due to the strict hearing acuity and symmetry criteria. Furthermore, the lack of significant findings for key lower limb gait measures (e.g., mean velocity, stride length) might be partially explained by the use of treadmill walking instead of more naturalistic over-ground walking (Hicheur & Berthoz, 2005). Furthermore, the maximum belt speed on the treadmill (1.0 m/s) may have inhibited fast walking in younger adults which may have influenced their larger DTCs in lower limb gait measures. This is further supported by the lack of significant findings in gait velocity and only limited observations concerning cadence. As well, the use of treadmill walking and joystick use may have deterred older participants from adjusting their gait speed, which may have limited the number of significant effects on cadence and velocity measures.

Future studies need to place greater emphasis on the examination of upper-body movement in combination with lower gait parameters because both types of gait measures are affected by concurrent task performance. Furthermore, researchers should consider whole-body locomotion to attain a more holistic assessment of locomotion, particularly when the concurrent task requires other sensory processes that might affect posture, such as listening. Future work should also focus on the recruitment of a third group of older adults with hearing loss to better understand the role of compensation and task prioritization under clinical levels of sensory impairment.

Conclusion

In conclusion, our findings are consistent with past research that suggests a linkage between sensory, cognitive, and sensorimotor function in old age (Li & Lindenberger, 2002; Lin, 2011; Lin et al., 2011; Lindenberger & Baltes, 1997; Viljanen et al., 2009a; Viljanen et al., 2009b). Importantly, this study reports novel experimental evidence that complements the extant epidemiological association data linking hearing loss and mobility. Our findings provide empirical support for the posture first principle wherein older adults prioritize stable walking over cognitive performance. Our data also provide novel insight into the importance of upper body postural control, specifically average head pitch, during a complex multitalker task. The findings suggest that older adults who are better aligned might be better at listening; consequently they might be less susceptible to falls.

The current findings also lead to several clinical implications. First, auditory and cognitive measures should be considered in routine assessments of older persons at risk for developing gait impairments (Holtzer, et al., 2012). Effective intervention for hearing loss, such as hearing aids or assistive listening devices, should be provided by health care professionals in order to help improve auditory processing, thus freeing up resources for other tasks such as postural control, which utilize higher-order cognitive functions (Desjardins & Doherty, 2014; Pichora-Fuller & Singh, 2006; Rumalla, Karim, Hullar, 2015). Given the association between poor hearing and falls risk, management of hearing loss might improve the functional status and well-being in the elderly (Viljanen et al., 2009a). It is shown that hearing aids improved completion time of the TUG among other measures of mobility (Bugnariu, 2015). In addition, rehabilitation that involves cognitive training, exercise, and physical activity are found to improve cognition and improve balance (Bherer, 2015). Recent research showed that treadmill training in a VR environment improved mobility, reduced the risk of falls, and enhanced cognitive function and dual-task ability in older adults (Mirelman et al., 2013; Mirelman et al., 2010). The use of ecologically valid tools such as VR shows promise as a way to improve mobility and listening performance in older adults with sensory loss. Training new hearing aid users to gradually increase their listening complexity via VR or multi-tasking exercises may better prepare them for actual hearing aid use in their daily lives and potentially facilitate hearing aid adoption.

References

Amboni, M., Barone, P., & Hausdorff, J. M. (2013). Cognitive contributions to gait and falls: Evidence and implications. *Movement Disorders*, *28*(11), 1520-1533. doi:10.1002/mds.25674

Anstey, K. J., Hofer, S. M., & Luszcz, M. A. (2003). A latent growth curve analysis of late-life sensory and cognitive function over 8 years: Evidence for specific and common factors underlying change. *Psychology and Aging*, *18*(4), 714-726. doi:10.1037/0882-7974.18.4.714

Anstey, K., Stankov, L., & Lord, S. (1993). Primary aging, secondary aging, and intelligence. *Psychology and Aging*, *8*(4), 562-570. doi:10.1037/0882-7974.8.4.562

Atkinson, H. H., Rosano, C., Simonsick, E. M., Williamson, J. D., Davis, C., Ambrosius, W. T., Rapp, S. R., Cesari, M., Newman, A. B., Harris, T. B, Rubin, S. M., Yaffe, K., Satterfield, S., & Kritchevsky, S. B. (2007). Cognitive function, gait speed decline, and comorbidities: The health, aging and body composition study. *Journals of Gerontology Series A Biological Sciences and Medical Sciences*, *62*(8), 844-850.

Balota, D. A., Dolan, P. O., & Duchek, J. M. (2000). Memory changes in healthy older adults. In E. Tulving & F. I. M. Craik (Eds.), *The Oxford handbook of memory* (2nd Ed., pp. 395-410). New York, NY: Oxford University Press.

Baltes, P. B., & Baltes, M. M. (1990). Psychological perspectives on successful aging: The model of selective optimization with compensation. In P. B Baltes & M. M. Baltes (Eds.), *Successful aging: Perspectives from the behavioral sciences* (pp. 1-34). Cambridge, NY: Cambridge University Press.

Baltes, P. B., & Lindenberger, U. (1997). Emergence of a powerful connection between sensory and cognitive functions across the adult life span: A new window to the study of cognitive aging? *Psychology and Aging*, *12*(1), 12-21. doi:10.1037/0882-7974.12.1.12

Baltes, P. B., & Mayer, K. U. (1999). *The Berlin aging study: Aging from 70 to 100*. Cambridge, UK: Cambridge University Press.

Barry, E., Galvin, R., Keogh, C., Horgan, F., & Fahey, T. (2014). Is the timed up and go test a useful predictor of risk of falls in community dwelling older adults: A systematic review and meta-analysis. *BMC Geriatrics*, *14*(1), 1-14. doi:10.1186/1471-2318-14-14

Binder, E. F., Storandt, M., & Birge, S. J. (1999). The relation between psychometric test performance and physical performance in older adults. *Journal of Gerontology – Series A Biological Sciences and Medical Sciences*, *54*(8), M428-M432.

Bherer, L. (2015). Cognitive plasticity in older adults: Effects of cognitive training and physical exercise. *Annals of the New York Academy of Sciences*, *1337*(1), 1-6. doi:10.1111/nyas.12682

Blauert, J. (1997). *Spatial hearing: The psychophysics of human sound localization*. Cambridge, MA: MIT Press.

Ble, A., Volpato, S., Zuliani, G., Guralnik, J. M., Bandinelli, S., Laurentani, F., Bartali, B., Maraldi, C., Fellin, R., & Ferrucci, L. (2005). Executive function correlates with walking speed in older persons: The InChianti study. *Journal of the American Geriatrics Society*, *53*(3), 410-415. doi:10.1111/j.1532-5415.2005.53157.x

Bolia, R. S., Nelson, W. T., Ericson, M. A., & Simpson, B. D. (2000). A speech corpus for multitalker communications research. *The Journal of the Acoustical Society of America*, *107*(2), 1065-1066. doi:10.1121/1.428288

Bregman, A. S. (1990). *Auditory scene analysis*. Cambridge, MA: MIT Press.

Bronkhorst, A. W. (2000). The cocktail party phenomenon: A review of research on speech intelligibility in multi-talker conditions. *Acustica*, *86*(1), 117-128.

Bronkhorst, A. W., & Plomp, R. (1989). Binaural speech intelligibility in noise for hearing-impaired listeners. *The Journal of the Acoustical Society of America*, *86*(4), 1374-1383.

Bronkhorst, A. W., & Plomp, R. (1988). The effect of head-induced interaural time and level differences on speech intelligibility in noise. *Journal of the Acoustical Society of America*, *83*(4), 1508-1516.

Brown, L. A., & Woollacott, M. H. (1998). The effects of aging on the control of posture and locomotion in healthy older adults: An emphasis on cognition. *Psychologische Beitrage*, *40*, 27-43.

Butler, E. E., Druzin, M., & Sullivan, E. V. (2006). Gait adaptations in adulthood: Pregnancy, aging, and alcoholism. In J. Rose and J. G. Gamble (Eds.), *Human walking* (3rd Ed., pp. 131-147). Philadelphia, PA: Lippincott Williams & Wilkins.

Bugnariu, N. (2015, June). The effect of different types of hearing aids on postural control. In K. Li (Chair), *Impact of hearing impairment on postural control in old age*. Symposium conducted at the meeting of the International Society for Posture & Gait Research, Seville, Spain.

Chen, H.-C., Schultz, A. B., Ashton-Miller, J. A., Giordani, B., Alexander, N. B., & Guire, K. E. (1996). Stepping over obstacles: Dividing attention impairs performance of old more than young adults. *Journal of Gerontology – Series A Biological Sciences and Medical Sciences*, *51*(3), M116-M122.

Cherry, E. C. (1953). Some experiments on the recognition of speech, with one and with two ears. *The Journal of the Acoustical Society of America*, *25*(5), 975-979.

Committee on Hearing, Bioacoustics, and Biomechanics, Commission on Behavioural and Social Sciences and Education, National Research Council (CHABA; 1988). Speech understanding and aging. *The Journal of the Acoustical Society of America*, *83*(3), 859-895.

Coppin, A. K., Shumway-Cook, A., Saczynski, J. S., Patel, K. V., Ble, A., Ferrucci, L., & Guralnik, J. M. (2006). Association of executive function and performance of dual-task physical tests among older adults: Analyses from the InChianti study. *Age and Ageing*, *35*(6), 619-624. doi:10.1093/ageing/afl107

Craik, R. (1989). Changes in locomotion in the aging adult. In M. H. Woollacott and A. Shumway-Cook (Eds.), *Development of posture and gait across the life span*, (pp. 176-201). Columbia, SC: University of South Carolina Press.

Craik, F. I. M., & Byrd, M. (1982). Aging and cognitive deficits. The role of attentional resources. In F. I. M. Craik & S. Trehub (Eds.), *Aging and cognitive processes* (pp. 191-211). New York, NY: Springer.

Delis, D. C., Kaplan, E., & Kramer, J. H. (2001). *D-KEFS Technical Manual*. San Antonio, TX: The Psychological Corporation.

Desjardins, J. L. & Doherty, K. A. (2014). The effect of hearing aid noise reduction on listening effort in hearing-impaired adults. *Ear and Hearing*, *35*(6), 600-610.

Durlach, N. I., Mason, C. R., Kidd, G., Arbogast, T. L., Colburn, H. S., & Shinn-Cunningham, B. G. (2003). Note on informational masking. *Journal of the Acoustical Society of America*, *113*(6), 2984-2987.

Duquesnoy, A. J. (1983). The intelligibility of sentences in quiet and in noise in aged listeners. *The Journal of the Acoustical Society of America*, *74*(1136), 87-96. doi:10.1121/1.390037

Early Treatment Diabetic Retinopathy Study Research Group. (1985). Photocoagulation for diabetic macular edema. Early Treatment Diabetic Retinopathy Study report number 1. *Archives of Ophthalmology*, *103*(12), 1796-1806.

Ericson, M. A, Brungart, D. S., & Simpson, B. D. (2004). Factors that influence intelligibility in multitalker speech displays. *International Journal of Aviation Psychology*, *14*(3), 313-334.

Fransen, E., Lemkens, N., van Laer, L., & van Camp, G (2003). Age-related hearing impairment (ARHI): Environmental risk factors and genetic prospects. *Experimental Gerontology*, *38*(4), 353-359. doi:10.1016/S0531-5565(03)00032-9

Freyman, R. L., Balakrishnan, U., & Helfer, K. S. (2001). Spatial release from informational masking in speech recognition. *The Journal of the Acoustical Society of America*, *109*, 2112-2122. doi:10.1121/1.1354984

Gabell, A., & Nayak, U. S. L. (1984). The effect of age on variability in gait. *Journal of Gerontology*, *39*(6), 662-666.

Gerson, L. W., Jarjoura, D., & McCord, G. (1989). Risk of imbalance in elderly people with impaired hearing or vision. *Age and Ageing*, *18*(1), 31-34. doi:10.1093/ageing/18.1.31

Gosselin, P. A., & Gagné, J.-P. (2011). Older adults expend more listening effort than young adults recognizing speech in noise. *Journal of Speech, Language, and Hearing Research*, *54*(3), 944-958. doi:10.1044/1092-4388(2010/10-0069)

Grady, C. (2012). The cognitive neuroscience of ageing. *Nature Reviews Neuroscience*, *13*(7), 491-505. doi:10.1038/nrn3256

Grose, J. H. (1996). Binaural performance and aging. *Journal of the American Academy of Audiology*, *7*(3), 168-174.

Grose, J. H., Poth, E. A., & Peters, R. W. (1994). Masking level differences for tones and speech in elderly listeners with relatively normal audiograms. *Journal of Speech and Hearing Research*, *37*(2), 422-428.

Hausdorrf, J. M., Schweiger, A., Herman, T., Yogev-Seligmann, G., & Giladi, N. (2008). Dual-task decrements in gait: Contributing factors among healthy older adults. *Journal of Gerontology – Series A Biological Sciences and Medical Sciences*, *63*(12), 1335-1343.

Hausdorff, J. M., Yogev, G., Springer, S., Simon, E. S., & Giladi, N. (2005). Walking is more like catching than tapping: Gait in the elderly as a complex cognitive task. *Experimental Brain Research*, *164*(4), 541-548. doi:10.1007/s00221-005-2280-3

Hausdorff, J. M., Balash, J., & Giladi, N. (2003). Effects of cognitive challenge on gait variability in patients with Parkinson's disease. *Journal of Geriatric Psychiatry and Neurology*, *16*(1), 53-58.

Hausdorff, J. M., Rios, D. A., & Edelberg, H. K. (2001). Gait variability and fall risk in community-living older adults: A 1-year prospective study. *Archives of Physical Medical and Rehabilitation*, *82*(8), 1050-1056. doi:10.1053/apmr.2001.24893

Helfer, K. S. (1992). Aging and the binaural advantage in reverberation and noise. *Journal of Speech and Hearing Research*, *35*(6), 1394-1401.

Hicheur, H., & Berthoz, A. (2005). How do humans turn? Head and body movements for the steering of locomotion. *Proceedings of 2005 5th IEEE-RAS International Conference on Humanoid Robots*, 265-270. doi:10.1109/ICHR.2005.1573578

Hirasaki, E., Kubo, T., Nozawa, S., Matano, S., & Matsunaga, T. (1993). Analysis of head and body movements of elderly people during locomotion. *Acta Oto-Laryngologica*, *113*(501), 25-30. doi:10.3109/00016489309126208

Holtzer, R., Wang, C., & Verghese, J. (2012). The relationship between attention and gait in aging: Facts and fallacies. *Motor Control*, *16*(1), 64-80.

Holtzer, R., Mahoney, J. R., Izzetoglu, M., Izzetoglu, K., Onaral, B., & Verghese, J. (2011). fNIRS study of walking and walking while talking in young and old individuals. *Journal of Gerontology – Series A Biological Sciences and Medical Sciences*, *66A*(8), 879-887. doi:10.1093/gerona/glr068

Holtzer, R., Verghese, J., Xue, X., & Lipton, R. B. (2006). Cognitive processes related to gait velocity: Results from the Einstein Aging Study. *Neuropsychology*, *20*(2), 215-223. doi:10.1037/0894-4105.20.2.215

Humes, L. E. (1996). Speech understanding in the elderly. *Journal of the American Academy of Audiology*, *7*, 161-167.

Huxhold, O., Li, S.-C., Schmiedek, F., & Lindenberger, U. (2006). Dual-tasking postural control: Aging and the effects of cognitive demand in conjunction with focus of attention. *Brain Research Bulletin*, *69*(3), 294-305. doi:10.1016/j.brainresbull.2006.01.002

Jensen, A. R. (1965). Scoring the Stroop test. *Acta Psychologica*, *24*(5), 398-408.

Kado, D. M., Huang, M. -H., Nguyen, C. B., Barrett-Connor, E., & Greendale, G. A. (2007). Hyperkyphotic posture and risk of injurious falls in older persons: The Rancho Bernardo Study. *Journal of Gerontology - Series A Biological Sciences and Medical Sciences*, *62*(6), 652-657.

Kahneman, N. (1973). *Attention and effort*. Englewood Cliffs, NJ: Prentice-Hall.

Kemper, S., Herman, R. E., & Lian, C. H. T. (2003). The costs of doing two things at once for young and older adults: Talking while talking, finger tapping, and ignoring speech or noise. *Psychology and Aging*, *18*(2), 181-192. doi:10.1037/0882-7974.18.2.181

Kidd, G., Arbogast, T. L., Mason, C. R., & Gallun, F. J. (2005). The advantage of knowing where to listen. *The Journal of the Acoustical Society of America*, *118*(6), 3804-3815. doi:10.1121/1.2109187

Koehnke, J., & Besing, J. M. (2001). The effects of aging on binaural and spatial hearing. *Seminar in Hearing*, *22*(3), 241-252. doi:10.1055/s-2001-15629

Kramer, A. F., Hahn, S., & Gopher, D. (1999). Task coordination and aging: Explorations of executive control processes in the task switching paradigm. *Acta Psychologica*, *101*(2-3) 339-378.

Lajoie, Y., & Gallagher, S. P. (2004). Predicting falls within the elderly community: Comparison of postural sway, reaction time, the Berg balance scale and the Activities-specific Balance Confidence (ABC) scale for comparing fallers and non-fallers. *Archives of Gerontology and Geriatrics*, *38*(1), 11-26. doi:10.1016/S0167-4943(03)00082-7

Lajoie, Y., Teasdale, N., Bard, C., & Fleury, M. (1996). Upright standing and gait: Are there changes in attentional requirements related to normal aging? *Experimental Aging Research*, *22*(2), 185-198.

Lajoie, Y., Teasdale, N., Bard, C., & Fleury, M. (1993). Attentional demands for static and dynamic equilibrium. *Experimental Brain Research*, *97*(1), 139-144. doi:10.1007/BF00228824

Li. K. Z. H., Abbud, G. A., Fraser, S. A., & DeMont, R. G. (2012). Successful adaptation of gait in healthy older adults during dual-task treadmill walking. *Aging, Neuropsychology, and Cognition*, *19*(1-2), 150-167. doi:10.1080/13825585.2011.628375

Li. K. Z. H., Krampe, R. T., & Bondar, A. (2005). An ecological approach to studying aging and dual-task performance. In R. W. Engle, G. Sedek, U. von Hecker, and D. N. McIntosh (Eds.), *Cognitive limitations in aging and psychopathology,* (pp. 190-218). New York, NY: Cambridge University Press.

Li, K. Z. H., & Lindenberger, U. (2002). Relations between aging sensory/sensorimotor and cognitive functions. *Neuroscience and Biobehavioral Reviews*, *26*(7), 777-783. doi:10.1016/S0149-7634(02)00073-8

Li, K. Z. H., Lindenberger, U., Freund, A. M., & Baltes, P. B. (2001). Walking while memorizing: Age-related differences in compensatory behavior. *Psychological Science*, *12*(3), 230-237.

Li, L., Daneman, M., Qi, J. G., & Schneider, B. A. (2004). Does the information content of an irrelevant source differentially affect spoken word recognition in younger and older adults? *Journal of Experimental Psychology: Human Perception and Performance*, *30*(6), 1077-1091. doi:10.1037/0096-1523.30.6.1077

Li, L., Simonsick, E. M., Ferrucci, L., & Lin, F. R. (2013). Hearing loss and gait speed among older adults in the United States. *Gait & Posture*, *38*(1), 25- 29. doi:10.1016/j.gaitpost.2012.10.006

Lichtenberger, E. O., & Kaufman, A. S. (2013). *Essentials of WAIS-IV assessment*. Hoboken, NJ: John Wiley & Sons.

Lin, F. R., Ferrucci, L., Metter, E. J., An, Y., Zonderman, A. B., & Resnick, S. M. (2011). Hearing loss and cognition in the Baltimore Longitudinal Study of Aging, *Neuropsychology*, *25*(6), 763-770. doi:10.1037/a0024238

Lin, F. R., Thorpe, R., Gordon-Salant, S., & Ferrucci, L. (2011). Hearing loss prevalence and risk factors among older adults in the United States. *Journals of Gerontology – Series A Biological Sciences and Medical Sciences*, *66A*(5), 582-590. doi:10.1093/gerona/glr002

Lindenberger, U., & Ghisletta, P. (2009). Cognitive and sensory declines in old age: Gauging the evidence for a common cause. *Psychology and Aging*, *24*(1), 1-16. doi:10.1037/a0014986

Lindenberger, U., Marsiske, M., & Baltes, P. B. (2000). Memorizing while walking: Increase in dual-costs from young adulthood to old age. *Psychology and Aging*, *15*(3), 417-436. doi:10.1037//0882-7974.15.3.417

Lindenberger, U., Scherer, H., & Baltes, P. B. (2001). The strong connection between sensory and cognitive performance in old age: Not due to sensory acuity reductions operating during cognitive assessment. *Psychology and Aging*, *16*(2), 196-205. doi:10.1037/08827974.16.2.196

Lindenberger, U., & Baltes, P. B. (1997). Intellectual functioning in old and very old age: Cross-sectional results from the Berlin aging study. *Psychology and Aging*, *12*(3), 410-432. doi:10.1037/0882-7974.12.3.410

Lindenberger, U., & Baltes, P. B. (1994). Sensory functioning and intelligence in old age: A strong connection. *Psychology and Aging*, *9*(3), 339-355.

Lövdén, M., Schaefer, S., Pohlmeyer, A. E., & Lindenberger, U. (2008). Walking variability and working-memory load in aging: A dual-process account relating cognitive control to motor control performance. *Journal of Gerontology – Series B Psychological Sciences and Social Sciences*, *63*(3), P121-P128.

Lövdén, M., Ghisletta, P., & Lindenberger, U. (2004). Cognition in the Berlin Aging Study (BASE): The first 10 years. *Aging, Neuropsychology, and Cognition*, *11*(2-3), 104-133. doi:10.1080/13825580490510982

Lundin-Olsson, L., Nyberg, L., & Gustafson, Y. (1997). 'Stops walking when talking' as a predictor of falls in elderly people. *Lancet*, *349*(9052), 617.

Madden, D. J. (1990). Adult age differences in attentional selectivity and capacity. *European Journal of Cognitive Psychology*, *2*(3), 229-252. doi:10.1080/09541449008406206

Maki, B. E. (1997). Gait changes in older adults: Predictors of falls or indicators of fear? *Journal of the American Geriatric Society*, *45*(3), 313-320.

Maylor, E. A., & Wing, A. M. (1996). Age differences in postural stability are increased by additional cognitive demands. *Journals of Gerontology - Series B Psychological Sciences and Social Sciences*, *51*(3), 143-154.

McGough, E. L., Kelly, V. E., Logsdon, R. G., McCurry, S., Cochrane, B. B., Engel, J. M., & Teri, L. (2011). Associations between physical performance and executive function in older adults with mild cognitive impairment: Gait speed and the timed 'Up & Go' test. *Physical Therapy*, *91*(8), 1198-1207. doi:10.2522/ptj.20100372

Mirelman, A., Rochester, L., Reelick, M., Nieuwhof, F., Pelosin, E., Abbruzzese, G., Dockx, K., Nieuwboer, A., & Hausdorff, J. M. (2013). V-TIME: A treadmill training program augmented by virtual reality to decrease fall risk in older adults: Study design of a randomized controlled trial. *BMC Neurology*, *13*(15), 1-12.

Mirelman, A., Maidan, I., Herman, T., Deutsch, J. E., Giladi, N., & Hausdorff, J. M. (2010). Virtual reality for gait training: Can it induce motor learning to enhance complex walking and reduce falls risk in patients with Parkinson's disease? *Journal of Gerontology – Series A Biological Sciences and Medical Sciences*, *66A*(2), 234-240. doi:10.1093/gerona/glq201

Mulder, T., Berndt, H., Pauwels, J., & Nienhuis, B. (1993). Sensorimotor adaptability in the elderly and the disabled. In G. E. Stelmach & V. Hömberg (Eds.), *Sensorimotor impairment in the elderly* (pp. 413-426). Dordrecht, Netherlands: Kluwer Academic.

Murphy, D. R., Daneman, M., & Schneider, B. A. (2006). Why do older adults have difficulty following conversation? *Psychology and Aging*, *21*(1), 49-61. doi:10.1037/0882-7974.21.1.49

Nasreddine, Z. S., Phillips, N. A., Bédirian, V., Charbonneau, S., Whitehead, V., Collin, I., Cummings, J. L., & Chertkow, H. (2005). The Montreal Cognitive Assessment (MOCA): A brief screening tool for mild cognitive impairments. *Journal of the American Geriatrics Society*, *53*(4), 695-699. doi:10.1111/j.1532-5415.2005.53221.x

Neider, M. B., Gaspar, J. G., McCarley, J. S., Crowell, J. A., Kaczmarski, H., & Kramer, A. F. (2011). Walking and talking: Dual-task effects on street crossing behavior in older adults. *Psychology and Aging*, *26*(2), 260-268. doi:10.1037/a0021566

Newman, A. B., Simonsick, E. M., Naydeck, B. L., Boudreau, R. M., Kritchevsky, S. B., Nevitt, M. C., Pahor, M., Satterfield, S., Brach, J. S., Studenski, S. A., & Harris, T. B. (2006). Association of long-distance corridor walk performance with mortality, cardiovascular disease, mobility limitation, and disability. *Journal of the American Medical Association*, *295*(17), 2018-2026. doi:10.1001/jama.295.17.2018

Pashler, H. (1993). Dual-task interference and elementary mental mechanisms. In D. Meyer and S. Kornblum (Eds.), *Attention and performance* (pp. 245-264). Cambridge, MA: MIT Press.

Parham, K., Lin, F. R., Coelho, D. H., Sataloff, R. T., & Gates, G. A. (2013). Comprehensive management of presbycusis: Central and peripheral. *Otolaryngology – Head and Neck Surgery*, *148*(4), 537-539. doi:10.1177/0194599813477596

Persad, C. C., Giordani, B., & Chen, H. -C., Ashton-Miller, J. A., Alexander, N. B., Wilson, C. S., Berent, S., Guire, K., & Schultz, A. B. (1995). Neuropsychological predictors of complex obstacle avoidance in healthy older adults. Journal of Gerontology – Series B Psychological Sciences and Social Sciences, *50*(5), P272-P277.

Pichora-Fuller, M. K., & Singh, G. (2006). Effects of age on auditory and cognitive processing: Implications for hearing aid fitting and audiologic rehabilitation. *Trends in Amplification*, *10*(1), 29- 59. doi:10.1177/108471380601000103

Pichora-Fuller, M. K. (2003a). Cognitive aging and auditory information processing. *International Journal of Audiology*, *42*, 2S26-2S32.

Pichora-Fuller, M. K. (2003b). Processing speed and timing in aging adults: Psychoacoustics, speech perception, and comprehension. *International Journal of Audiology*, *42*(Suppl. 1), S59-S67.

Pichora-Fuller, M. K. (1997). Language comprehension in older listeners. *Journal of Speech-Language Pathology and Audiology*, *21*(2), 125-142.

Pichora-Fuller, M. K., Schneider, B. A., & Daneman, M. (1995). How young and old adults listen to and remember speech in noise. *Journal of the Acoustical Society of America*, *97*(1), 593-608. doi:10.1121/1.412282

Pichora-Fuller, M. K., & Schneider, B. A. (1992). The effect of interaural delay of the masker on masking-level differences in young and old adults. *Journal of the Acoustical Society of America*, *91*, 2129-2135.

Pichora-Fuller, M. K., & Schneider, B. A. (1991). Masking-level differences in the elderly: A comparison of antiphasic and time-delay dichotic conditions. *Journal of Speech and Hearing Research*, *34*(6), 1410-1422.

Podsiadlo, D., & Richardson, S. (1991). The timed 'up and go': A test of basic functional mobility for frail elderly persons. *Journal of the American Geriatrics Society*, *39*(2), 142-148.

Powel, L. E., & Myers, A. M. (1995). The activities-specific balance confidence (ABC) scale. *Journal of Gerontology – Series A Biological Sciences and Medical Science*, *50A*(1), M28-M34.

Rabbitt, P. (1991). Mild hearing loss can cause apparent memory failures which increase with age and reduce with IQ. *Acta Oto-Laryngologica*, *111*(S476), 167-176. doi:10.3109/00016489109127274

Rabbitt, P. M. (1968). Channel-capacity, intelligibility and immediate memory. *The Quarterly Journal of Experimental Psychology*, *20*(3), 241-248.

Rumalla, K., Karim, A. M., & Hullar, T. E. (2015). The effect of hearing aids on postural stability. *Laryngoscope*, *125*(3), 720-723. doi:10.1002/lary.24974

Salthouse, T. A. (1996). The processing-speed theory of adult age differences in cognition. *Psychological Review*, *103*(3), 403-428.

Salthouse, T. A. (1991). Mediation of adult age differences in cognition by reductions in working memory and speed of processing. *Psychological Science*, *2*(3), 179-183. doi:10.1111/j.1467-9280.1991.tb00127.x

Schneider, B. A., & Pichora-Fuller, M. K. (2000). Implications of perceptual deterioration for cognitive aging research. In F. I. M. Craik and T. A. Salthouse (Eds.), *The handbook of aging and cognition*, (2nd Ed., pp. 155 – 219). Mahwah, NJ: Lawrence Erlbaum Associates.

Schneider, B. A. (1997). Psychoacoustics and aging: Implications for everyday listening. *Journal of Speech-Language Pathology and Audiology*, *21*, 111-124.

Schuknecht, H. F. (1964). Further observations on the pathology of presbycusis. *Archives of Otolaryngology*, *80*, 369-382.

Seidler, R. D., Bernard, J. A., Burutolu, T. B., Fling, B. W., Gordon, M. T., Gwin, J. T., Kwak, Y., & Lipps, D. B. (2010). Motor control and aging: Links to age-related brain structural, functional, and biochemical effects. *Neuroscience and Biobehavioral Reviews*, *34*, 721 733. doi:10.1016/j.neubiorev.2009.10.005

Sheridan, P. L., Solomont, J., Kowall, N., & Hausdorff, J. M. (2003). Influence of executive function on locomotor function: Divided attention increases gait variability in Alzheimer's disease. *Journal of the American Geriatrics Society*, *51*(11), 1633-1637. doi:10.1046/j.1532-5415.2003.51516.x

Shumway-Cook A., Brauer, S., & Woollacott, M. (2000). Predicting the probability for falls in community-dwelling older adults using the timed up and go test. *Physical Therapy*, *8*0(9), 896-903.

Shumway-Cook, A., Baldwin, M., Polissar, N. L., & Gruber, W. (1997a). Predicting the probability for falls in community-dwelling older adults. *Physical Therapy*, *77*(8), 812-819.

Shumway-Cook, A., Woollacott, M., Kerns, K. A., & Baldwin, M. (1997b). The effects of two types of cognitive tasks on postural stability in older adults with and without a history of falls. *Journals of Gerontology – Series A Biological Sciences and Medical Sciences*, *52*(4), M232-M240.

Shumway-Cook, A., & Woollacott, M. (1995). *Theory and applications*. Baltimore, MD: Wilkins & Wilkins.

Shunk, A. W., Davis, A. S., & Dean, R. S. (2007). Review of the Delis Kaplan Executive Function System (D-KEFS). *Applied Neuropsychology*, *13*(4), 275-279. doi:10.1207/s15324826an1304_9

Sinaki, M., Brey, R. H., Hughes, C. A., Larson, D. R., & Kaufman, K. R. (2005). Balance disorders and increased risk of falls in osteoporosis and kyphosis: Significance of kyphotic posture and muscle strength. *Osteoporosis International*, *16*(8), 1004-1010. doi:10.1007/s00198-004-1791-2

Singh, G., Pichora-Fuller, M. K., & Schneider, B. A. (2008). The effect of age on auditory spatial attention in conditions of real and simulated spatial separation. *Journal of the Acoustical Society of America*, *124*(2), 1294-1305. doi:10.1121/1.2949399

Spielberg, P. I. (1940). Walking patterns of old people: Cyclographic analysis. In N. A. Bernstein (Ed.), *Investigations on the biodynamics of walking, running, and jumping*. Moscow, Russia: Central Scientific Institute of Physical Culture.

Springer, S., Giladi, N., Peretz, C., Yogev, G., Simon, E. S., & Hausdorff, J. M. (2006). Dual-tasking effects on gait variability: The role of aging, falls, and executive function. *Movement Disorders*, *21*(7), 950-957. doi:10.1002/mds.20848

Statistics Canada. (2006). Participation and activity limitation survey 2006: Ottawa, ON. Retrieved May 31, 2015, from http://www.statcan.gc.ca/pub/89-628-x/89-628-x2009012-eng.pdf

Stroop, J. R. (1935). Studies of interference in serial verbal reactions. *Journal of Experimental Psychology*, *18*(6), 643-662. doi:10.1037/h0054561

Tinetti, M. E., Mendes de Leon, C. F., Doucette, J. T., & Baker, D. I. (1994). Fear of falling and fall-related efficacy in relationship to functioning among community-living elders. *Journal of Gerontology*, *49*(3), M140-M147.

Tun, P. A., McCoy, S., & Wingfield, A. (2009). Aging, hearing acuity, and the attentional costs of effortful listening. *Psychology and Aging*, *24*(3), 761-766. doi:10.1037/a0014802

Tun, P. A., O'Kane, G., & Wingfield, A. (2002). Distraction by competing speech in young and older adult listeners. *Psychology and Aging*, *17*(3), 453-467. doi:10.1037/0882-7974.17.3.453

Tun, P. A., & Wingfield, A. (1999). One voice too many: Adult age differences in language processing with different types of distracting sounds. *Journal of Gerontology - Series B Psychological Sciences and Social Sciences*, *54*(5), P317-P327.

Valentijn, S. A. M., van Boxtel, M. P. J., van Hooren, S. A. H., Bosma, H., Beckers, H. J. M., Ponds, R. W. H. M., & Jolles, J. (2005). Change in sensory functioning predicts change in cognitive functioning: Results from a 6-year follow-up in the Maastricht Aging Study.

Journal of the American Geriatrics Society, *53*(3), 374-380. doi:10.1111/j.1532-5415.2005.53152.x

Verghese, J., Kuslansky, G., Holtzer, R., Katz, M., Xue, X., Buschke, H., & Pahor, M. (2007). Walking while talking: Effect of task prioritization in the elderly. *Archives of Physical Medicine and Rehabilitation*, *88*(1), 50-53, doi:10.1016/j.apmr.2006.10.007

Verhaeghen, P., & Cerella, J. (2002). Aging, executive control, and attention: A review of meta-analyses. *Neuroscience and Biobehavioral Reviews*, *2*(7), 849-857. doi:10.1016/S0149-7634(02)00071-4

Verrel, J., Lövdén, M., Schellenbach, M., Schaefer, S., & Lindenberger, U. (2009). Interacting effects of cognitive load and adult age on the regularity of whole-body motion during treadmill walking. *Psychology and Aging*, *24*(1), 75-81. doi:10.1037/a0014272

Viljanen, A., Kaprio, J., Pyykkö, I., Sorri, M., Koskenvuo, M., & Rantanen, T. (2009a). Hearing acuity as a predictor of walking difficulties in older women. *Journal of the American Geriatrics Society*, *57*(12), 2282-2286. doi:10.1111/j.1532-5415.2009.02553.x

Viljanen, A., Kaprio, J., Pyykkö, I., Sorri, M., Pajala, S., Kauppinen, M., Koskenvuo, M., & Rantanen, T. (2009b). Hearing as a predictor of falls and postural balance in older female twins. *Journal of Gerontology – Series A Biological Sciences and Medical Sciences*, *64A*(2), 312-317. doi:10.1093/gerona/gln015

Walling, A. D., & Dickson, G. M. (2012). Hearing loss in older adults. *American Family Physician*, *85*(12), 1150-1156.

Watson, C. S. (1987). Uncertainty, informational masking and the capacity of immediate auditory meaning. In W. A. Yost and C. S. Watson (Eds.), *Auditory processing of complex sounds* (pp. 267-277). Hillsdale, NJ: Lawrence Erlbaum Associates.

Wechsler, D. (2008). *Wechsler Adult Intelligence Scale: WAIS-IV Technical and Interpretive Manual*. San Antonio, TX: The Psychological Corporation.

Wechsler, D. (1997). *Wechsler Adults Intelligence Scale: WAIS-III Manual*. San Antonio, TX: The Psychological Corporation.

Wilson, R. H. (2003). Development of a speech-in-multitalker-babble paradigm to assess word-recognition performance. *Journal of the American Academy of Audiology*, *14*(9), 453-470.

Wingfield, A., Tun, P. A., & McCoy, S. L. (2005). Hearing loss in older adulthood: What it is and how it interacts with cognitive performance. *Current Directions in Psychological Science*, *14*(3),144-148. doi:10.1111/j.0963-7214.2005.00356.x

Wingfield, A., & Tun, P. (2001). Spoken language comprehension in older adults: Interactions between sensory and cognitive change in normal aging. *Seminars in Hearing*, *22*(3), 287-301. doi:10.1055/s-2001-15632

Woollacott, M., & Shumway-Cook, A. (2002). Attention and the control of posture and gait: A review of an emerging area of research. *Gait and Posture*, *16*(1), 1 – 14. doi:10.1016/S0966-6362(01)00156-4

Woollacott, M. H., & Jensen, J. L. (1996). Posture and locomotion. In H. Heuer & S. W. Keele (Eds.), *Handbook of perception and action: Motor skills* (pp. 333 – 403). London,UK: Academic Press.

Yogev-Seligmann, G., Hausdorff, J. M., & Giladi. N. (2012). Do we always prioritize balance when walking? Towards an integrated model of task prioritization. *Movement Disorders*, *27*(6), 765-770. doi:10.1002/mds.24963

Yogev-Seligmann, G., Rotem-Galili, Y., Mirelman, A., Dickstein, R., Giladi, N., & Hausdorff, J. M. (2010). How does explicit prioritization alter walking during dual-task performance? Effects of age and sex on gait speed and variability. *Physical Therapy*, *90*(2), 177-186. doi:10.2522/ptj.20090043

Zacks, R. T., Hasher, L., & Li. K. Z. H. (2000). Human memory. In T. A. Salthouse & F. I. M. Craik (Eds.), *The handbook of aging and cognition* (2nd Ed., pp. 293-357). Mahwah, NJ: Lawrence Erlbaum Associates.

Appendix A

History 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. Age:___________

2. Height: _______________

3. Weight: _______________

4. Gender: *(circle response)* (1) Male (2) Female

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

6. 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

Language:

7. Place of Birth:____

8. Languages Spoken (in order of fluency): _________________________________

9. Primary Language/Language of Choice:________________________________

10. Language at home:___________________ 11. At Work:____________________

12. Language of Education:____________________________

13. At what age did you first learn English? __________________

14. At what age did you become fluent in it?__________________

15. A) 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

B) List of degrees obtained (e.g., BA, MA): ____________________________

Employment:

16. A) What is or was your main occupation? __________________________

B) Are you retired? . . . . NO / SEMI / YES
Date when you retired: ________ (year) ____________ (month)

C) Was it ever noisy at work? . . . . .NO / YES
If **YES**, did you use ear protection? . . . . NO / SOMETIMES / YES

D) Were you ever in the military? . . . . NO / YES

E) Did /do you have noisy hobbies (e.g., carpentry, ski-doo, etc.)? . . . . NO / YES
What kind: ____

Hearing and Music:

17. A) Have you ever taken private music lessons?. NO / YES
If **YES**: For how many years? ____
How old were you when you stopped taking lessons? ____________________
Do you now play or sing regularly? . . . . NO / YES

B) Do you play a musical instrument by ear? . . . . NO / YES

C) Even if you did not take private music lessons, was there ever a time when you played an instrument or sang on a regular basis? . . . . NO / YES
If **YES**: For how many years? ____
Do you now play or sing regularly?. . . . . NO / YES
How old were you when you stopped playing/singing regularly?
____

Ignore this question if they answered YES to having taking private music lessons. Write N/A

D) Would you describe yourself as 'musically inclined'?. . . . . .NO / YES

E) Do you have ringing in your ears?. . . . .SOMETIMES / ALWAYS / NEVER
If **YES**, which ear(s)?. . . . . BOTH / LEFT / RIGHT

F) Did a family member have a hearing loss before old age?. . . . . NO / YES
Relationship to you? ____

G) Do you often get colds?. . . . . NO / YES

H) Do you have allergies? . . . . .NO / YES

I) Do you often get ear infections? . . . . .NO / YES

J) Can you hear the doorbell? . . . . .NO / YES

K) Can you have a phone conversation without difficulty?. . . . . NO / YES

L) When you hear a sound are you sometimes unsure where it is coming from?
NO / YES

M) Can you carry on a conversation with one other person when you are in a noisy place, such as a restaurant or at a party?. . . . . NO / YES

N) Do you feel that any difficulty with your hearing limits or hampers your personal or social life?. . . . . .NO / YES

O) Does difficulty with your hearing ever upset you? . . . . .NO / YES
If **YES**, please describe: ____
____
____

Vision:

18. A) Do you have:
Glaucoma . . . . .NO / YES
Cataract(s) . . . . NO / YES
Macular degeneration . . . . .NO / YES

B) Have you ever had eye surgery for:
Glaucoma . . . . .NO / RIGHT / LEFT Date:________________
Cataract(s) . . . . .NO / RIGHT / LEFT Date:________________
Macular degeneration . . . .NO / RIGHT / LEFT Date:________________
Corneal/lens transplants . . NO / RIGHT / LEFT Date:________________
Laser eye surgery . . . . NO / RIGHT / LEFT Date:________________

C) Do you currently receive medical treatment for your eyes? . . . . NO / YES
If **YES**, what kind? ____

D) Have you ever seen a doctor for an eye injury? . . . . NO / YES
Describe: ____

19. Have you ever been unconscious, had a head injury or had blackouts?
A) NO / YES
B) Cause:____
C) Duration:____
D) Treatment:____
E) Outcome:____

20. Have you 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 :

21. a) A Stroke? b) Transient ischemic attack?	NO / YES NO / YES	When?
22. Heart disease?	NO / YES	Nature (MI, angina, narrowing of arteries):
23. High blood pressure?	NO / YES	Is it controlled?
24. Bypass surgery?	NO / YES	
25. Other Surgery? 26. Seizures?	NO / YES NO / YES	Nature: Age Onset:______ Frequency:___________ Cause:__________ Treatment:___________
27. Epilepsy?	NO / YES	
28. a) Diabetes? b) Insulin dependent?	NO / YES NO / YES	Type I / Type II Age of Onset:___________________________ Treatment:_____________________________
29. Thyroid disease?	NO / YES	
30. Frequent headaches?	NO / YES	Tension / migraine
31. Dizziness?	NO / YES	
32. Trouble walking? Unsteadiness	NO / YES	
33. Arthritis?	NO / YES	
34. Any injuries to the lower limb? (e.g. hip, knee, ankle)	NO / YES	

35. Serious illness (e.g. liver disease)?	NO / YES	
36. Neurological disorders?	NO / YES	
37. Exposure to toxic chemicals (that you know of)?	NO / YES	
38. Anxiety?	NO / YES	
39. (Other) psychological difficulties?	NO / YES	
40. Hormone replacement?	NO / YES	
41. Steriods?	NO / YES	

40. Medication: Please list the medication you are currently taking and any other medication that you have taken in the past year I know Carmen is using a list of common medications that the participant can choose from. That might make things easier for you and the participant!

Type of medication	Reason for consumption	Duration of consumption and 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:

44. Action Video Games

During the past 6 months how many days per week did you play ACTION video games? (e.g., Call of Duty; Halo; Counter Strike; Gears of War; Grand Theft Auto; Tomb Raider; Resident Evil 6; The Last of Us; Dead Island etc.)

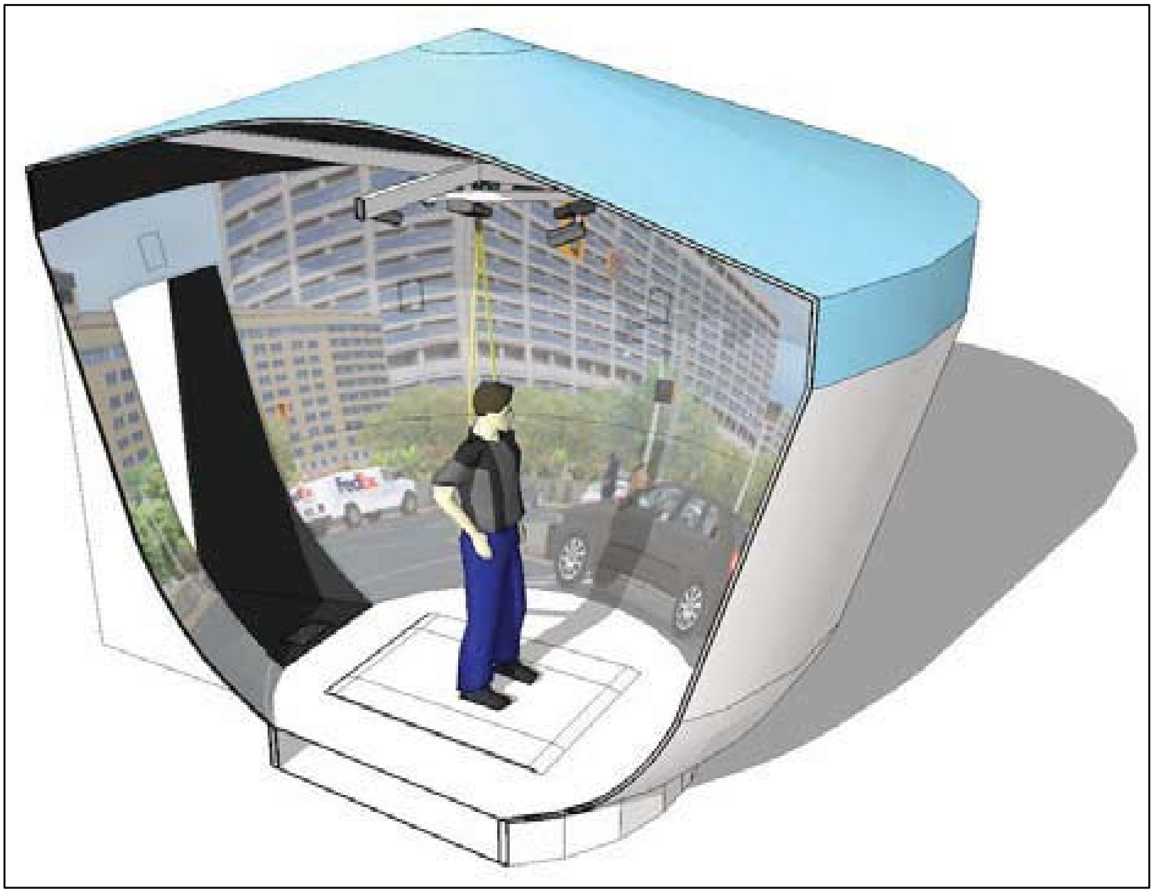
____

On the days where you played, approximately how many hours a day did you play ACTION video games?

____

Appendix B

Interior view of Streetlab.



Appendix C

All counterbalancing orders utilized in the study.

Order	Block 1	Block 2	Block 3	Block 4	Block 5	Block 6	Block 7	Block 8	Block 9	Block 10
1	Single-Task Listening 100% Probability	Single-Task Listening ≤75% Probability	Single-Task Walking	Dual-Task 100% Probability	Dual-Task ≤75% Probability	Dual-Task 100% Probability	Dual-Task ≤75% Probability	Single-Task Listening 100% Probability	Single-Task Listening ≤75% Probability	Single-Task Walking
2	Single-Task Listening ≤75% Probability	Single-Task Listening 100% Probability	Single-Task Walking	Dual-Task ≤75% Probability	Dual-Task 100% Probability	Dual-Task ≤75% Probability	Dual-Task 100% Probability	Single-Task Listening ≤75% Probability	Single-Task Listening 100% Probability	Single-Task Walking
3	Single-Task Walking	Single-Task Listening 100% Probability	Single-Task Listening ≤75% Probability	Dual-Task 100% Probability	Dual-Task ≤75% Probability	Dual-Task 100% Probability	Dual-Task ≤75% Probability	Single-Task Walking	Single-Task Listening 100% Probability	Single-Task Listening ≤75% Probability
4	Single-Task Walking	Single-Task Listening ≤75% Probability	Single-Task Listening 100% Probability	Dual-Task ≤75% Probability	Dual-Task 100% Probability	Dual-Task ≤75% Probability	Dual-Task 100% Probability	Single-Task Walking	Single-Task Listening ≤75% Probability	Single-Task Listening 100% Probability

Appendix D

Significant differences between the presentation of the first and second block for the same condition in each age group.

	Younger Adults				Older Adults			
	M	*SD*	*M*	*SD*	*M*	*SD*	*M*	*SD*
Performance Variable	Block A		Block B		Block A		Block B	
Listening task								
ST100%	0.66	0.28	0.79	0.14	0.46	0.23	0.63	0.24
ST75%	0.18	0.58	0.44	0.16	0.31	0.15	0.41	0.16

Note. ST100% = Single-task listening 100% probability. ST75% = Single-task listening ≤75% probability.

Appendix E

Significant differences between the presentation of the first and second block for the same condition in each age group.

	Younger Adults				Older Adults			
	M	*SD*	*M*	*SD*	*M*	*SD*	*M*	*SD*
Performance Variable	Block A		Block B		Block A		Block B	
PK head roll STW	-	-	-	-	16.03	16.90	12.80	15.02
AVG step width DT75%	0.18	0.06	0.19	0.06	-	-	-	-
AVG stride length STW	-	-	-	-	0.50	0.05	0.52	0.05
AVG stride length DT100%	-	-	-	-	0.50	0.05	0.51	0.05
AVG cadence STW	97.78	8.97	95.75	7.72	-	-	-	-
AVG stride time STW	-	-	-	-	1.41	0.11	1.46	0.13
Stride time variability STW	0.10	0.02	0.11	0.03	-	-	-	-
Stride time variability DT100%	0.11	0.04	0.12	0.06	-	-	-	-

Note. PK = Peak, AVG = Average. STW = Single-task walking. DT100% = Dual-task 100% probability. DT75% = Dual-task ≤75% probability.