Involvement of Cognitive Resources in Sensory and Sensorimotor Functioning with Age

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Abstract

Involvement of Cognitive Resources in Sensory and Sensorimotor Functioning with Age

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Epidemiological research indicates a link between hearing loss and poor mobility (Lin & Ferrucci, 2012; Viljanen et al., 2009). One explanation for this association is cognitive compensation, wherein older adults compensate for hearing loss and declines in mobility by recruiting higher-level cognitive resources. A growing body of research using various approaches demonstrates that cognitive resources are involved in both hearing and mobility with age. Our work complements these studies by using experimental, intervention and modeling techniques to investigate how these domains relate in an aging population.

Using an experimental approach, older adults and older adults with hearing loss completed a cognitive-motor dual-task protocol, in which they performed an auditory working memory task and a balance recovery task singly or concurrently. Older adults with mild hearing loss showed disproportionately greater dual-task costs on the auditory working memory task, particularly when auditory challenge was added. Given the involvement of cognitive resources in challenging dual-task conditions and particularly among a hearing loss population, the second study took a cognitive enhancement approach. Specifically, older adults with and without hearing loss were given either

simultaneous or sequential cognitive-physical training formats. While sequential training appeared to benefit performance on the auditory working memory task, older adults with hearing loss appeared to improve on this same task regardless of format. To complement these group-wise effects we took a structural equation modeling approach using data pooled from the two previous studies to examine individual differences in hearing and cognition which might influence mobility. An additional consideration was the impact of self-efficacy. It was found that the association between greater hearing loss and reduced mobility was mediated by cognitive status, and that self-efficacy in the hearing domain may be an important contributor to balance confidence.

Taken together, the current work points to the importance of cognitive resources in both sensory and motor aging, particularly among older adults with age-related hearing loss. As such, the work suggests that cognitive remediation may be a useful complement to traditional hearing and mobility rehabilitation. Moreover, self-efficacy appears to be an important contributor in understanding the relation between hearing loss and mobility.

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Contribution of Authors

For all three papers, in collaboration with my supervisor Dr. Karen Li, I designed the research question and experiment, set up the experimental paradigm, performed data collection (where applicable) and statistical analyses, and wrote the manuscript. Additional contributions of other coauthors are discussed below.

Paper 1

Dan Aponte helped with data collection and filtering of the raw data while Dr. Nancy St.-Onge provided extensive consultation with respect to setting up the experimental design and protocol. Dr. Natalie Phillips provided the stimuli for the auditory working memory task. All coauthors contributed to the conceptual interpretation of the findings and provided input on the final manuscript.

Paper 2

Laurence Lai was the other graduate student on the training project and therefore was heavily involved in designing the experiment and research question and in data collection. Drs. Maxime Lussier and Bherer provided us with the cognitive iPad training task used in the study. Dr. J.-P. Gagné provided consultation regarding the auditory assessment and presentation of stimuli. All coauthors contributed to the conceptual interpretation of the findings and provided input on the final manuscript.

Paper 3

As data was already collected for this study, the majority of contributions from coauthors was with respect to interpreting the conceptual findings and reviewing the first manuscript draft.

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CHAPTER ONE

GENERAL INTRODUCTION

Population Aging

Over the past 40 years, the population of older adults (i.e., 65 years and older) in Canada has been steadily growing, increasing from 8% to 14% of the population between 1971 to 2010. This growth is expected to continue such that between 2015 to 2021, the number of older adults is projected to exceed the number of children aged 14 and younger for the first time ever (Statistics Canada, 2011). Aging is associated with changes in sensory and sensorimotor functioning. Specifically, according to Statistics Canada, 78% of adults over the age of 60 experience hearing loss, which is more prevalent among men than women. Moreover, within this older adult population, 30-35% of people aged 65 and older have a form of hearing loss and this increases to 40-50% for people aged 75 and older (National Institute on Deafness and Other Communication Disorders, 1997). In addition to challenges in hearing, falls are also of significance to the aging population such that approximately 1 in 3 seniors aged 65 years and older are likely to fall at least once per year and falls are one of the leading causes of injury-related hospitalizations (Statistics Canada, 2014). These two domains are also connected such that hearing loss is associated with a greater incidence of falls (Lin & Ferruci, 2012; Viljanen et al., 2009) even when accounting for vestibular function (Lin & Ferruci, 2012). Additionally, both hearing loss and falls have broader emotional and social consequences including social isolation, depression, safety issues, and reduced income and employment opportunities (Bizier, Contreras, & Walpole, 2016; Brennan, Gombac, & Sleightholm, 2009) as well as poor quality of life and functional limitations (Dalton et al., 2003, Mitchell et al., 2011).

Cognitive Aging

With advancing age, individuals experience declines in cognition, which impact day-to-day functioning. While some abilities such as implicit memory, world knowledge, and verbal abilities remain stable and may even increase over the lifespan, normative declines in other domains of long-term memory, processing speed, working memory and executive function have been observed (Craik & Salthouse, 2000; 2008; Park & Reuter-Lorenz, 2009; West, 1996).

Executive functions are of particular interest to researchers because of their role in everyday physical and cognitive tasks and contribution to independent functioning (Baddeley, 1986; Norman & Shallice, 1986). Contemporary models of executive function suggest a multifactorial construct consisting of several independent but correlated abilities such as working memory, inhibition, task switching and divided attention (Engle, Tuholski, Laughlin, & Conway, 1999; Miyake et al., 2000). Different measures have been used to measure executive functions including "complex span" tasks, the Stroop inhibition task and dual-task paradigms and generally suggest declines in these domains with age (e.g., Bopp & Verhaeghen, 2005; Li, Vadaga, Bruce, & Lai, 2017; Wasylyshyn, Verhaeghen, & Sliwinski, 2011).

In tandem with behavioural changes, researchers have demonstrated age-related changes to brain size and vasculature. With age, the volume of the brain decreases at a rate of around 5% per decade after the age of 40 (Peters, 2006) with decline becoming steeper with age (Dennis & Cabeza, 2008). Although volumetric decreases have been noted in gray and white matter, the brain does not change uniformly across regions, such that the prefrontal region is most affected by gray matter loss followed by the parietal lobe. Additionally, rate of decline also differs between sub-regions. For example, the medial temporal lobes which contain the hippocampus and entorhinal cortex show increased atrophy with age and within frontal and parietal lobes, inferior regions decline more sharply. Similarly, white matter declines throughout the brain affecting most prominently the frontal lobes. Importantly, these changes in prefrontal regions are associated with decreased performance on executive function tasks as well as on measures of processing speed, reasoning and memory (Dennis & Cabeza, 2008; Raz, 1996).

Interestingly, in contrast to what might be expected given the existing behavioural and structural data, neural activity does not globally decrease with age. Functional imaging techniques have revealed both increases and decreases in brain activation (Dennis & Cabeza, 2008; Park & Reuter-Lorenz, 2009), with different patterns observed between younger and older adults. Several theories have been developed to explain these patterns of activation including the HAROLD model (Cabeza, 2002), which suggests that older adults recruit more bilateral prefrontal regions than younger adults when performing cognitive tasks. This increased activation can be linked to improved performance on behavioural tasks such as measures of memory attention, perception, inhibition and working memory (Cabeza et al., 2004; Cabeza, 2002; Gutchess et al., 2005) and is present among high-performing older adults (Dennis & Cabeza, 2008). Together, these results suggest a process of compensation rather than dedifferentiation.

A second theory to account for preserved cognitive performance in the context of neural decline is the Scaffolding Theory of Aging (STAC). This model states that behavioural performance reflects the joint influences of brain aging and compensatory scaffolding or the recruitment of additional brain regions and circuits. Like the HAROLD Model (Cabeza, 2002), this theory describes increased bilateral activation among older adults as well as increased activation of frontal regions. Within this framework, scaffolding is the brain's typical response to challenge and although present among younger adults, increases with age to maintain cognitive function. Therefore, levels of performance are malleable and subject to enrichment, but constrained by biological factors such as age. Scaffolding is not static across the lifespan as it can be supported through lifestyle factors such as exercise or cognitive training (Hertzog, Kramer, Wilson, & Lindenberger, 2008; Park & Reuter-Lorenz, 2009). A more recent review of longitudinal aging research prompted the authors to revise the STAC model and incorporate life-course factors (i.e., accumulation of experiences and states) that impact the structure and function of the brain as well as the development of compensatory scaffolding (STAC-R; Reuter-Lorenz & Park, 2014).

Other researchers (Li & Lindenberger, 2002) have proposed that since cognitive resources are increasingly involved in the hearing and motor tasks with age, brain aging and compensatory scaffolding might also impact the sensory and sensorimotor abilities. Within this framework of cognitive compensation, declining peripheral functioning are compensated for via the recruitment of higher-order cognitive resources. Evidence for the involvement of cognitive resources in both auditory and motor functioning has been demonstrated in epidemiological, experimental, neuroimaging and intervention work as discussed below.

Hearing and Aging

Theory and cognitive involvement. With age, hearing may be impacted by several age-normative changes including both peripheral and cognitive factors including declines in cognition and changes to more central auditory processes (Martin & Jerger, 2005; Pichora-Fuller, Schneider, & Daneman, 1995; Schneider et al., 2010). Specifically, older adults experience elevated hearing thresholds particularly in the high frequency range, losses in spectral and temporal acuity, and possible loss of neural synchrony in the auditory pathways. If these losses are not too severe and the auditory signal is sufficient, these changes will likely only have a minimal effect on simple speech recognition in quiet conditions. However, although hearing loss can account for speech-related problems in quiet, these peripheral changes can only account for some of the challenges that older adults experience in noisy or challenging listening conditions (Schneider et al., 2010).

To properly comprehend sound and speech, individuals must locate and segregate sound sources to focus on the stimulus of interest and ignore irrelevant information in the environment. In addition to locating and separating out sound sources, speech comprehension is affected by temporal processing, which is partly under the control of the central auditory nervous system. Since speech is a complex sound varying over time, listeners must process brief, time-varying acoustic information to understand individual phonemes, process rapid acoustic information about individual phonemes in a sequence of changing acoustic cues, and follow the overall timing of a spoken message (Gordan-Salant, Fitzgibbons, & Yeni-Komshian, 2011). With age, the auditory system becomes slower and more asynchronous, which can affect processing time and inter-aural timing respectively (Pichora-Fuller, 2003).

Cognitive theorists have suggested that in addition to a degrading signal due to peripheral changes, older adults may be more vulnerable to intrusions from irrelevant or distracting stimuli due to age-related changes in working memory (Brebion, 2003; DeDe, Caplan, Kemtes, & Waters, 2004; Tun, Wingfield, & Stine, 1991;Van der Linden et al., 1999), slowed speed of processing (Stine, 1995; Stine & Hindman, 1994; Tun, Wingfield, Stine, & Mecsas, 1992; Wingfield, Poon, Lombardi, & Lowe, 1985), and a deficit in inhibitory processes (Hasher & Zacks, 1988; Hasher, Zacks, & May, 1999). Therefore, researchers have investigated the contribution of cognitive resources to hearing using varied methodologies.

Correlational. To this end, epidemiological work has demonstrated an association between hearing and cognition such that sensory and cognitive abilities are more strongly associated in older compared to middle-aged adults (Baltes & Lindenberger, 1997). Moreover, objectively assessed hearing is correlated with measures of processing speed (Lin, 2011), memory and executive function (Lin et al., 2011). Hearing was also associated with an increased risk of cognitive impairment, which was linearly associated with the severity of the individual's baseline hearing loss (Lin et al., 2013). Using modeling techniques, others have demonstrated that compared to healthy controls, older adults with clinically diagnosed sensory impairment show stronger relations between cognitive abilities and behavior-related everyday functioning as well as self-reported mastery of everyday activities and the environment (Heyl & Wahl, 2012). Turning to brain correlates, neuroimaging suggests that hearing impairment is independently associated with reduced volumes in the auditory cortex (Eckert, et al., 2012; Husain, et al., 2010; Peelle, et al., 2011), as well as accelerated volume declines in whole brain and regional volumes in the right temporal lobe (Lin et al., 2014).

Sensory load. Another approach to investigating the interaction between cognitive status and hearing is by manipulating the sensory load, for example by changing the characteristics of speech or by presenting speech in noise (e.g., multispeaker babble). Interestingly, multivariate work suggests that central processing and cognition, rather than peripheral hearing, predicts listening performance in noise conditions (Anderson et al., 2013). In such studies, older adults benefitted more from contextual cues compared to younger adults (Pichora-Fuller, 1995) and tended to use linguistic knowledge (i.e., semantic and syntactic context of the sentence) to compensate for deficits in speech-in-noise perception (Wingfield, 1996), suggesting a compensatory cognitive process. However, there appears to be a cost associated with this compensatory mechanism. For example, when auditory memory items are presented in noise, age and noise exhibit similar negative effects on long-term memory performance. One possible explanation is that the decrease in processing resources with aging is associated with less effective encoding into secondary memory (Murphy, Craik, Li, & Schneider, 2000). Similarly, accelerating speech to challenge processing speed requirements or decreasing the presentation level of an auditory working memory task is more detrimental with age, hearing loss, and increasing task demands (Baldwin & Ash, 2012; Wingfield, McCoy, Peelle, Tun, & Cox, 2006).

Dual-task. Another approach to investigating the role of cognition is through a dual-task approach wherein two tasks are administered singly (single-task) and then simultaneously (dual-task) with the assumption that if there is a drop in performance from single- to dual-task conditions on either task, they are thought to rely on a common resource. Administering a dual-task paradigm under quiet listening conditions reveals that listeners with hearing loss, especially older adults, showed larger secondary task costs while recalling a list of words even though the stimuli were presented at a sound intensity that allowed correct word identification (Tun, McCoy, & Wingfield, 2009). When this same dual-task approach is used with noise, older adults demonstrate a greater amount of listening effort to recognize speech in noise when compared with younger adults. This cost is further exacerbated with hearing loss both under identical Signal-to-Noise Ratio (SNR) conditions and when groups are tested at the same level of performance by equating for accuracy by adjusting the SNR (Gagne, Besser, & Lemke, 2017). Specifically, presenting words in noise resulted in lower memory performance and this decline in memory mimics memory deficits observed when participants performed the same task in quiet conditions, concurrent with a secondary attentional non-auditory task (Heinrich, Schneider, & Craik, 2008). Similarly, others have demonstrated that extracting information from noise comes at a cost to performance on a secondary non-auditory task (Gosselin & Gagne, 2011). This increased cognitive involvement is supported through fMRI recordings taken during dual-tasking which reveal increased activation in prefrontal regions among older adults particularly in challenging conditions (Wong et al., 2009).

Intervention. Another approach to understanding the contributions to age-related hearing loss is through interventions which either correct for peripheral hearing loss or strengthen cognitive resources. One approach comes from clinical audiological intervention wherein older adults diagnosed with hearing impairment are treated with amplification using hearing aids. Within this population, cognitive scores (i.e., working memory, general intelligence) correlated with scores on speech tests even after amplification with hearing aids (Pichora-Fuller, 2009). Furthermore, among first time hearing aid users, higher baseline cognitive scores were associated with an increased performance on a speech recognition task in noise when performed with amplification devices (Gatehouse, Naylor, & Elberling, 2003, 2006; Lunner, 2003). Moreover, working memory training and auditory training consisting of phenome discrimination in quiet and noise resulted in generalized improvements on measures of self-reported hearing, competing speech and complex cognitive tasks which assess executive function (Ferguson & Henshaw, 2015).

Self-efficacy. Self-efficacy can be defined as an individuals' perceptions of their abilities in specific domains which will determine whether they engage in particular activities (Bandura, 1997). In addition to normative age-related declines, negative stereotypes of aging may contribute to the mismatch between self-perceptions of abilities of function and actual abilities (Chasteen, Pichora-Fuller, Dupuis, Smith, & Singh, 2015). With respect to hearing, listening self-efficacy may be more strongly associated with hearing handicap and perceived difficulty in any given situation rather than performance on objective clinical measures of hearing (Smith, Pichora-Fuller, Watts, & La More, 2011). In other words, even if an individual has the ability or capacity to meet the demands of a given situation, allocating resources depends in part on the person's evaluation of their capacity and willingness to expend the effort (Pichora-Fuller, 2016). Additionally, hearing impairment is associated with reduced functioning in daily life and specifically with self-reported hearing handicap, communication difficulties (Dalton et al., 2003) and self-perceived social engagement restrictions (Gopinath et al., 2012).

Mobility and Aging

Definition and measurement techniques. Balance is a generic term used to describe postural dynamics that individuals employ to prevent themselves from falling (Winter, 1995) while posture can be defined as the control of the body's position in space for the purposes of balance and orientation (Woollacott & Shumway-Cook, 2002). Posture is typically assessed using standing or static balance tasks (e.g., double support standing) and dynamic balance, wherein individuals respond to an environmental event such as a platform perturbation (Paillard & Noe, 2015). Performance is typically quantified in terms of changes in posture over time, such as center of mass (COM) and center of foot pressure (COP) distance, area or range of excursion, or variability of movement. Other parameters of posture include measurement of muscle activations (electromyography) or brain activation during real or imagined balance tasks. Lastly, performance can be described by the type of postural strategy used in response to environmental events, such as platform perturbations (Paillard & Noe, 2015). With aging, upright postural sway generally increases (Bergamin, 2014) and is linked to subsequent falls (Maki, Holliday, & Fernie, 1990). In response to dynamic balance tasks, older adults generate a larger COM area and are more likely to initiate a stepping strategy at lower levels of challenge (Brown et al., 1999; Jensen, Brown, & Woollacott, 2011; Tsai, Hiseh, & Yang, 2014).

Although a distinct component of mobility, gait can be conceptualized as a dynamic balance task wherein an individual's goal is now to move their body outside of the base of support while preventing falls (Winter, 1995). Gait has been assessed using many different tasks such as walking at self-selected speeds, treadmill walking, obstacle avoidance or using walkways with embedded sensors to measure more specific time- and spatially-based aspects of gait. Using these tasks, numerous parameters have been used to describe gait including gait speed, cadence (steps/minute), step length (average distance between each successive footfall), and gait variability (standard deviation or coefficient of variation of step time or length). Like posture, both structural and functional neuroimaging have been used to index gait during real or imagined tasks. With age, older adults typically demonstrate greater gait variability, decreased walking speed (Callisaya et al., 2010), shorter stride lengths, decreased stride frequency and a more rigid posture (Kovacs, 2005) compared to younger adults. They also tend to take shorter steps (Medell & Alexander, 2000) or adopt a more conservative gait pattern, such as reduced speed (Chen, Ashton-Miller, Alexander, & Schultz, 1991) in challenging environments.

Some of the age-related changes in posture and gait can be linked to physical causes such as sarcopenia, which refers to a reduction in muscle mass and strength with age (Laurenti et al., 2003) thus reducing the force of muscle contraction, which in turn affects proprioception (Hurley, Rees, & Newham, 1998). In addition, older adults often experience a reduction in joint flexibility (Nolan, Nitz, Choy, & Illing, 2010). Although previously conceptualized as reflexive and automatic, recent work suggests that in addition to changes associated with physical functioning, balance and gait require attentional resources with age, which vary depending on the task used, the age of the individual and their balance abilities (Woollacott & Shumway-Cook, 2002). Therefore, different research approaches have been used to investigate the involvement of cognition in mobility.

Correlational. Correlational work demonstrates that lower executive function performance is associated with decreased gait speed and increased gait variability, particularly in more cognitively challenging conditions (Ble et al., 2005; Hausdorff, Yogev, Springer, Simon, & Giladi, 2005; Holtzer, Verghese, Xue, & Lipton, 2006), as well as self-reported incidence of recurrent falls (Anstey, Caldwell, Wood, Kerr, & Lord, 2009). Moreover, lower levels of cognitive functioning at baseline increased the risk of developing a mobility impairment later in life (Buchman et al., 2011).

Experimental dual-tasking. Complementing the correlational work, dual-task studies have demonstrated significant attentional demands associated with balance and gait among older adults (Woollacott & Shumway-Cook, 2002). When performing dual-task gait, older adults demonstrate decreased performance on concurrent walking and memory tasks, for example when ambulating around obstacles (Chen et al., 1996; Lindenberger, Marsiske, & Baltes, 2000). In static balance conditions, older adults exhibit greater dual-task costs than young adults on either the balance task (e.g., increased CoP area), the concurrent cognitive task, or both (Boisgontier et al., 2013). However, with increasing motor challenge, these attentional costs become more pronounced in the cognitive domain (Brown et al., 1999; Li, Krampe, & Bondar, 2005; Little & Woollacott, 2014; Redfern, Muller, Jennings, & Furman, 2002; Verghese et al., 2007). This phenomenon has been termed postural prioritization (Li et al., 2005) and refers to the tendency for older adults to prioritize mobility particularly if motor tasks are ecologically valid.

Another experimental approach involves manipulating sensory inputs such as altering proprioceptive information using softer surfaces (e.g., compliant foam surface, high-pile carpet with rubber padding) or standing with eyes closed (Redfern, Moore, & Yarsky, 1997; Teasdale, Bard, LaRue, & Fleury, 1993). Using these approaches, researchers have demonstrated that older adults are more susceptible to reduced proprioceptive input as indexed by increased postural sway. Together these results suggest that when conflicting sensory information is introduced (Redfern, Jennings, Martin, & Furman, 2001), maintaining posture requires more attentional demands. Specifically, it has been hypothesized that age-related declines in inhibition might account for age-related difficulties in sensory integration (combining visual, vestibular, and proprioceptive inputs) while balancing (Redfern, et al., 2001).

Interestingly, not all secondary tasks are detrimental to mobility and can sometimes be facilitative. Specifically, a U-shaped function has been observed wherein balancing or walking concurrent with a basic cognitive task may improve motor performance, although these dual-task benefits turn into costs as cognitive complexity increases (Huxhold, Li, Schmiedek, & Lindenberger, 2006; LaRoche, Greenleaf, Croce, & McGaughy, 2014; Lövden et al., 2008). One explanation is that simple cognitive loads are facilitative because devoting full attention to a highly automated mobility task is unnatural and detracts from motor coordination; however, at higher levels of cognitive interference this benefit is attenuated due to resource competition which becomes detrimental to motor performance (Fraizer & Mitra, 2008; Huxhold, et al., 2006).

Another method of quantifying posture performance is through electromyography (EMG) to assess muscle activity either during single-task balancing or with a concurrent cognitive task. Reduced amplitude of muscle activation has been noted in challenging dual-task conditions, particularly for older adults, further supporting the idea that fewer attentional resources are available for balance control with age (Rankin, Woollacott, Shumway-Cook, & Brown, 2000). Qualitative changes with age have also been noted in the balance strategies exhibited in response to perturbations. Specifically, when encountering dynamic postural challenges, such as an unpredictable platform movement (i.e., perturbation), typical postural recovery progresses from ankle, hip, to stepping strategies as perturbations become more challenging (Horak, Henry, & Shumway-Cook, 1997; Nashner & McCollum, 1985). However, not all balance strategies are equivalent in their cognitive demands: there is evidence of an attentional continuum of balance strategies, such that ankle flexion is more commonly exhibited during low demand situations, whereas hip or stepping strategies are expressed as cognitive load increases (Brown et al., 1999). With respect to strategy, older adults are more likely than younger adults to initiate a stepping strategy at lower levels of postural threat (Brown et al., 1999; Little & Woollacott, 2014) and demonstrated a greater cognitive cost under dual-task conditions with a stepping strategy compared to an ankle strategy, whereas young adults did not show this pattern (Brown, Shumway-Cook, & Woollacott, 1999).

Neuroimaging. Other researchers have linked structural and functional changes in the brain to performance on posture and gait tasks, which appear to involve both overlapping and distinct brain regions. Performance on postural tasks is negatively associated with cortical changes in the brain (e.g., brain atrophy; Papegaaij et al., 2014) and volume in gray matter regions such as the basal ganglia, superior posterior parietal cortex, and cerebellum which are correlated with balance difficulty (Rosano et al., 2007a). Decreased gait speed and higher gait variability are also associated with smaller overall cortical gray matter volume, but also specifically within the hippocampus and anterior cingulate gyrus as well as greater white matter hyper-intensities (Ezzati et al., 2015; Rosano et al., 2007a; Rosano, Brach, Studenski, Longstreth, & Newman, 2007b; Rosso et al., 2014).

Other approaches such as fMRI PET, EEG and functional near infrared spectroscopy (fNIRS) have been used to collect real-time recordings during balance and walking tasks. Using these techniques, researchers have demonstrated increased activation in the premotor cortex, prefrontal cortex, basal ganglia, cerebellum and brainstem, when subjects imagined themselves standing while lying in the scanner (Papegaaij, 2014). Additionally, older adults recruit cerebral networks involving temporal, prefrontal and subcortical regions to perform balance tasks, with increased activation observed during challenging dual-task conditions (e.g., unpredictable events, low sensory input; Wittenberg, Thompson, Nam, & Franz, 2017). Using time-sensitive EEG, researchers have demonstrated that cortical responses adapt in the context of cues suggesting that cognitive resources are involved in planning postural responses (Papegaaij, 2014) and that postural responses to unpredictable perturbations appear to be slowed or weakened with age particularly in the later, more controlled phases of the postural response (Maki & McIlroy, 2007).

Turning to gait, imagined locomotion activates an indirect pathway via the supplementary motor cortex and basal ganglia loop implicating the primary sensorimotor area, prefrontal area, and temporal lobe in more cognitively demanding gait protocols such as walking while talking (Holtzer et al., 2014). When performing gait tasks, there is an associated increase in cerebral oxygenation in the prefrontal cortex (PFC), premotor cortex and SMA with increasing dual-task attentional demands and in anticipation of the acceleration of gait. These changes are also modulated by age, disease status, and walking capacity (Holtzer et al., 2011; Holtzer et al., 2015; Mirelman et al., 2014).

Intervention. Several different approaches have been used to improve single- and dual-task gait and posture. Beyond physical and balance training, researchers have used computerized cognitive training which has been shown to reduce postural sway in single- and dual-task conditions (Fraser et al., 2017; Li et al., 2010). Similarly, cognitive training programs designed to improve executive function, attention, and memory have demonstrated benefit to gait speed during normal paced walking and dual-task walking (Smith-Ray et al., 2013; Verghese, Mahoney, Ambrose, Wang, & Holtzer et al., 2010).

Another approach combines physical and cognitive training in multimodal formats typically using one of two formats: sequential training where the two tasks are administered separately or simultaneous training where the two tasks are administered concurrently. Simultaneous training may be more advantageous as it trains real-life scenarios, reduces training time and costs (Theill et al., 2013) and trains coordination between cognitive and physical tasks (Zhu et al., 2016). On the other hand, simultaneous training may take attention away from the cognitive training task (Li, Lindenberger, Freund, & Baltes, 2001) meaning sequential training may be more advantageous as it allows for individuals to focus complete attention on training the cognitive and physical training tasks.

The literature comparing multimodal training to single domain training is mixed. Some have demonstrated increased efficacy of sequential (Zhu et al., 2016) and simultaneous training (Agmon, Belza, Nguyen, Logsdon, & Kelly, 2014) when compared to single domain training on dual-task outcomes with respect to gains on the cognitive, motor or both tasks (Agmon et al., 2014). Others (Desjardins-Crépeau, 2016; Fraser et al., 2017) have failed to find synergistic effects when comparing sequential physical (i.e., aerobic) and cognitive (i.e, dual-task) training to single domain training. Specifically, participants were randomized to one of three active treatment groups (i.e., cognitive, physical, cognitive + physical) or an active control group for 12 weeks of tri-weekly training. While all participants in the active treatment groups improved on outcomes of dual-task walking, postural sway, and functioning mobility, there was no additional benefit to training both tasks sequentially (Desjardins-Crépeau, 2016; Fraser et al., 2017).

Self-efficacy. Self-efficacy within the domain of mobility is often described by constructs such as balance confidence (Powell & Myers, 1995) or fear of falling (Scheffer, Schuurmans, van Dijk, van der Hooft, & de Rooij, 2008). Although objective balance performance is a significant contributor to balance confidence, it cannot fully account for all the variance in balance confidence (Hatch, Gill-Body, & Portney, 2003). Self-efficacy can also translate to behavioural outcomes in that decreased balance confidence can contribute to the avoidance of activities resulting in physical frailty, falls and loss of independence (Rand, Miller, Yiu, & Eng, 2011).

Hearing and Motor Aging

Hearing and motor aging are also connected in that individuals with hearing loss are at a greater risk for falls (Lin & Ferruci, 2012; Viljanen et al., 2009). Additionally, severity of hearing impairment is associated with higher prevalence of difficulties with walking and falls as well as decreased performance on several objective measures of postural control (Agmon, Lavie, & Doumas, 2016). Similarly, a recent observational study (Wollesen et al., 2017b) revealed that older adults with hearing loss showed reduced walking speed which was accompanied by decreased step length and increased cadence, particularly in challenging dual-task conditions. Although less work has explicitly measured hearing, motor and cognitive functioning together, some researchers have considered these domains simultaneously. Using virtual-reality to mimic everyday motor-sensory challenges, researchers have demonstrated that while all older adults appeared to prioritize the walking task, those with hearing loss demonstrated greater stride variability and lowered performance on the auditory cognitive task (Lau et al., 2016; Niebrowska et al., in press). Additionally, taking an intervention approach, others (Shayman, Earhart, & Hullar, 2017) have demonstrated improved gait and balance with assistive devices such as hearing aids and cochlear implants.

The Current Studies

In sum, a growing body of research suggests that both hearing and mobility increasingly rely on cognitive resources with age. Additionally, within this framework, increased hearing loss would negatively impact mobility performance and vice versa. Given the central role of cognition in both sensory and sensorimotor aging, the current studies aimed to investigate the role of cognition in both hearing and mobility domains among older adults using three different approaches.

Specifically, the first experimental study investigated the role of cognition by manipulating cognitive load and simulating age-related hearing loss using a dual-task cognitive-motor paradigm. Rather than increase cognitive load, the second study took an intervention approach using combined physical and cognitive training to strengthen cognitive resources with the goal of also increasing cognitive-motor dual-tasking. Lastly, the third study used modeling techniques to examine the relations between cognitive, mobility and hearing domains from an individual difference perspective and incorporating the concept of self-efficacy. Generally, we expected that older adults with hearing loss would show greater dual-task costs given the increased reliance on cognitive resources. We also anticipated that strengthening cognition would benefit dual-task outcomes measures, particularly among those with hearing loss. Lastly, we expected that hearing loss would be associated with decreased cognition and mobility.

CHAPTER TWO

STUDY 1

The Effects of Age and Hearing Loss on Dual-Task Balance and Listening

Abstract

Objectives: Among older adults, hearing loss is associated with an increased risk for falls. The aim of the present study was to experimentally investigate the cognitive compensation hypothesis, wherein decreased auditory and motor functioning are compensated by the recruitment of cognitive resources. **Method**: 29 younger adults (YA), 26 older adults (OA), and 32 older adults with age-related hearing loss (ARHL) completed a dual-task paradigm consisting of cognitive and balance recovery tasks performed singly and concurrently. The auditory stimuli were presented with or without background noise. **Results**: Both older adult groups performed significantly worse than YA on the cognitive task in noisy conditions and ARHL also demonstrated disproportionate negative effects of dual-tasking and noise. The kinematic data indicated that OA and ARHL demonstrated greater plantarflexion when compared with YA. Conversely, YA showed greater hip extension in response to dual-tasking. **Discussion**: The cognitive and balance results suggest that YA were able to flexibly allocate their attention between tasks, whereas ARHL exhibited prioritization of posture over cognitive performance.

Word count: 165 (max 200)

Key words: Motor Aging, Auditory Aging, Postural Recovery, Cognitive Compensation

Introduction

With age, older adults experience increasing difficulty with cognitive, physical and sensory functioning, which in turn affects social functioning and impacts independent living. Epidemiological work demonstrates that poorer hearing acuity is associated with an increased risk of falling (Lin & Ferrucci, 2012; Viljanen et al., 2009). With age, both auditory functioning and balance increasingly rely on cognitive resources to compensate for peripheral changes (Li & Lindenberger, 2002), suggesting that both domains compete for common cognitive resources. However, despite the accumulating correlational evidence, little experimental research exists investigating this association. The present study was designed to test this hypothesis using an auditory-motor dual-task paradigm with young, older, and older adults with age-related hearing loss.

Auditory aging

With age, hearing is impacted by both peripheral and cognitive changes (Schneider et al., 2010), such as elevated thresholds for tone detection in the high frequency range (i.e., 4000 Hz, 8000 Hz) and suprathreshold difficulties when auditory stimuli are presented in multi-speaker contexts and in environments with background noise (Schneider et al., 2010). Declines in cognitive and attentional processes such as inhibition, working memory, and processing speed also contribute to age-related difficulties in speech comprehension and auditory memory (Schneider et al., 2010).

Support for the association between cognitive and auditory aging can be found in experimental studies of speech perception wherein sensory load is manipulated. One common approach is to overlay target speech with background noise such as multi-speaker babble, which is more detrimental to older listeners' performance than to young, and might prompt a greater reliance on top-down processes (Pichora-Fuller et al., 2016). Importantly, this utilization of top-down resources in speech perception may come at a cost to other cognitive processes such as those needed for memory encoding (e.g., Murphy et al., 2000).

Another experimental strategy used to examine the cognitive contribution to hearing in old age is to add a concurrent task to the listening task (i.e., dual-tasking). For example, dual-task costs are exacerbated by aging and hearing loss during performance of an auditory recognition memory task (Gosselin & Gagné, 2011; Tun et al., 2009). Importantly, these patterns of age-differential cognitive costs persist even when the presentation level (in dB-A) is adjusted individually to control for hearing loss (e.g., Heinrich et al., 2008). Together, the available evidence indicates an increasing interaction between auditory and cognitive processing with age, and a greater reliance on cognitive capacity for those with hearing loss (Heyl & Wahl, 2012).

Motor Aging

Similar to the auditory aging findings, patterns of cognitive compensation have been observed during balance and gait as expressed with behavioural and neural indices (Seidler et al., 2009; Woollacott & Shumway-Cook, 2002; Yogev-Seligman, Hausdorff, & Giladi, 2008). Importantly, postural sway increases with age (Maylor & Wing, 1996), and is associated with subsequent falls (Maki et al., 1990). When encountering dynamic postural challenges, such as an unpredictable platform movement (i.e., perturbation), typical postural recovery progresses from ankle, hip, to stepping strategies as perturbations become more challenging (Horak et al., 1997; Nashner & McCollum, 1985). Compared to younger adults, older adults generate a greater center of mass (i.e., COM) sway (Tsai et al., 2014), which may be further exacerbated by postural threat or concurrent cognitive demands. In a study of postural recovery from a forward platform perturbation, older adults demonstrated a greater cognitive cost under dual-task conditions with a stepping strategy compared to an ankle strategy, whereas young adults did not show this pattern (Brown et al., 1999), suggesting that postural recovery strategies vary in their attentional demands.

Another notable age difference in motor strategy is that older adults tend to prioritize physical safety over cognitive performance in the context of cognitive-motor dual-tasking (Li et al., 2005). This pattern of prioritization has been termed the "posture first" response, and is evident in cognitive-motor dual-task studies when older adults show greater cognitive dual-task costs than young adults, but comparable motor costs. Others have found that within dual-task conditions, older adults exhibit less sensitivity to manipulations of cognitive task difficulty compared to younger adults, suggesting that they are less willing to relinquish resources to address increased cognitive demands (e.g., Lajoie, Teasdale, Bard, & Fleury, 1993).

In sum, the current research on mobility and aging strongly parallels the research on auditory aging, in showing an increasing role of cognitive resources to address sensory and motor declines. To merge these separate areas of research, our present thesis is that because both hearing and motor performance require greater cognitive capacity in aging, there is competition for compensatory cognitive resources, which may account for the extant correlations between hearing loss and mobility decline (Agmon et al., 2017; Lin & Ferrucci, 2012).

Current Study

To experimentally integrate the domains of auditory and motor aging, a dual-task method was used to challenge younger adults, normal hearing older adults, and older adults with age-related hearing loss. In line with the cognitive compensation view, we paired a challenging auditory working memory task with a postural recovery task, expecting that older adults with age-related hearing loss would show disproportionately greater dual-task costs than normal hearing young and older adults, due to greater reliance on cognitive resources with hearing loss. Listening difficulty was also manipulated by adding background noise to the auditory stimuli. Based on previous findings, we expected that under noisy listening conditions, both older adults and older adults with age-related hearing loss would perform more poorly on the auditory cognitive task than younger adults. Finally, in line with the posture first principle, we anticipated that both older adult groups would prioritize balance performance over performance on the auditory cognitive task due to the ecological value of maintaining one's balance, whereas young adults would be able to more flexibly distribute their attentional resources between the auditory task and the balance task.

Method

Participants

The total sample consisted of eighty-seven individuals: twenty-nine healthy younger adults (YA) between the ages of 18 and 30 years old (*M* = 21.83, *SD* = 3.01, females = 25) recruited through the Concordia University participant pool, twenty-six healthy older adults (OA) between the ages of 65 and 85 years old (*M* = 65.19, *SD* = 3.26, females = 20) and thirty-two older adults with age-related hearing loss (ARHL) between the ages of 65 and 85 years old (*M* = 70.75, *SD* = 5.76, females = 15) recruited through an existing senior participant pool at Concordia and advertisements in a local senior paper. ARHL participants were defined as having an average pure-tone hearing threshold between 25-40 dB HL (i.e., decibel hearing level; re: ANSI S3.6-2004), while normal hearing younger and older adults were defined as having an average pure-tone hearing threshold below 25 dB HL. YA received course credits and older adults received an honorarium. Exclusion criteria included the existence of any progressive medical conditions and the use of any medication affecting cognitive or balance abilities. Further exclusion criteria included suspected presence of mild cognitive impairment as defined by the Montreal Cognitive Assessment (MoCA < 26/30; Nasreddine et al., 2005), hearing aid use, and any self-reported difficulties in balance or mobility. Participants were also required to be fluent in English and have normal or corrected-to-normal visual acuity. Of the 141 participants screened, 54 were ineligible due to low MoCA scores, poor physical health, scheduling conflicts, or severity of hearing loss.

Materials

Session 1: Screening and background. A health and demographics questionnaire was administered by telephone to evaluate eligibility. Eligible participants underwent in-person tests of sensory, motor, and cognitive functioning. Measures used for screening purposes are marked below with an asterisk.

Cognitive measures. Global cognitive functioning was assessed using the Montreal Cognitive Assessment "MoCA"* (Nasreddine et al., 1996) with a score of 26/30 or greater indicating normal cognitive performance. Cognitive processing speed and working memory were assessed using the Coding (Digit Symbol) Task and Letter Number Sequencing subtests of the Wechsler Adult Intelligence Scale (WAIS-IV; Wechsler, 2008) respectively. Executive functioning was measured using the Trail Making subtest of the Delis Kaplan Executive Functioning Scale "D-KEFS" (Delis, Kaplan, & Kramer, 2001), which assesses visuomotor processing speed (Conditions 2 & 3) and task switching (Condition 4). To isolate the executive component of the task, the average time to complete the visuomotor processing speed conditions was subtracted from the task switching condition.

Sensory measures. Air-conduction pure-tone audiometry* was administered using a Maico (MA 42) audiometer to assess hearing acuity for group classification, and to derive an average pure-tone threshold, which was then used to determine the appropriate intensity at which to present the auditory experimental stimuli. Participants were presented with pure tones at varying frequencies (250-8000 Hz) following standard procedure. The mean detection threshold of hearing corresponded to the average of the tone detection thresholds assessed at 500, 1000, 2000 and 3000 Hz, in both ears. Participants were also administered the Listening Self Efficacy Questionnaire (LSEQ: Smith et al., 2011), as a subjective index of hearing ability.

Physical measures. Global mobility was assessed using the Dynamic Gait Index (DGI: Shumway-Cook et al., 1997), a multi-component assessment (e.g., turning, stair ascent). The maximum possible score on the DGI is 24 and scores of 19 or less have been related to increased incidence of falls in the elderly (Shumway-Cook et al., 1997). Mobility was further assessed using the Sit-to-Stand task (Puthoff, 2008), which measures total time to stand up five times from a seated position with their arms crossed. The Activities-Specific Balance Confidence Scale "ABC Scale" (Powell & Myers, 1995) assessed self-reported balance confidence during different activities.

Session 2: Experimental tasks.

Balance task. The balance task involved a custom made perturbation platform (H2W, California) that delivered perturbations in the forward direction for a distance of 50 mm at a maximum velocity of 130-135 mm/s and an acceleration of 600-650 mm/s^2 (Quant, Adkin, Staines, Maki, & McIlroy, 2004). These parameters were designed to produce a mild perturbation that would not elicit a stepping response. A motion capture system made up of 8 MX-T20 cameras sampling at 100Hz (Vicon Motion Systems Ltd., Oxford, U.K.) was used to measure 3-dimensional positioning of major landmarks on the body (i.e., legs, chest, arms, head) using a standard whole-body 35 marker placement protocol (Plug-in Gait) and four markers on the moving platform.

Participants stood on the platform with their feet positioned shoulder width apart. They were instructed to remain as stable as possible with their hands on their hips and look forward at a stationary target (7.5 x 2 cm) located 4.4 m away. During each 30 second trial, participants experienced zero, one, or two perturbations, in random order. Perturbations occurred in one of two time windows (i.e., the first or second time window). For trials with two perturbations (one in each time window), the second perturbation occurred no less than five seconds after first to allow for adequate recovery time. Three short beeps signaled the beginning of each trial and a single beep signaled the end of the trial.

Cognitive task. The auditory working memory "*n*-back" task (Kirchner, 1958) served as the experimental cognitive task. In each trial, participants were presented with fifteen pseudo-randomly ordered (without consecutive repetition) single digit numbers between one and ten excluding the two-syllable numeral seven at a fixed presentation rate of one digit per second. The stimuli were presented via insert headphones (E-A-RLINK 3A) at 50 dB greater than each participant's average pure-tone threshold, as determined in Session 1. Participants were asked to report the number presented one step prior to the currently presented number (1-back) while the tester recorded their verbal responses. Half the trials were presented in quiet and half were presented in background noise (i.e., multi-talker babble consisting of six people speaking simultaneously) at a fixed signal-to-noise ratio (SNR) of -6 dB.

Procedure

All participants were tested individually at the PERFORM Centre of Concordia University. In Session 1, participants completed the demographic questionnaire and background measures of cognition, mobility and audition. During Session 2, participants completed the experimental cognitive and balance tasks under single and dual-task conditions. Participants first practiced on each of the experimental tasks separately. Following practice, participants were administered blocks of five trials of the cognitive and balance tasks separately without feedback, followed by two dual-task blocks of five trials in which the 1-back and balance tasks were performed concurrently. Under the dual-task condition, participants were instructed to treat each task as equally important. Finally, single-task blocks of the balance and cognitive tasks were administered again. This entire sequence was performed twice – once under quiet conditions, and once under noise conditions. Participants were given a seated break between any consecutive blocks involving the balance task. The order of task (balance or cognitive task) and auditory condition (quiet or noise) was counterbalanced between participants.

Data Analyses

Balance Data. Raw trajectory data collected via the motion capture system were filtered with a recursive low-pass Butterworth filter at 6 Hz. The filtered data were then used to compute ankle and hip angular displacements in the sagittal plane (see Appendix A). The analysis window was five seconds long; one second before each perturbation onset and four seconds after. The ankle plantarflexion amplitude refers to the most plantarflexion (i.e., foot pointed down) compared to the participant's baseline standing position prior to the perturbation. The hip extension amplitude refers to the most hip extension (i.e., sway-back or leaning backwards) compared to the participant's baseline standing position prior to the perturbation.

Cognitive Data. Cognitive performance was defined as the total number of correct responses identified in a given trial (maximum of 14 correct per trial). The number of correct responses was then summed across all ten trials per condition and converted to a percentage. To further explore the degree of interference from the secondary motor task, dual-task costs were calculated for the cognitive data by subtracting dual-task scores from single-task scores in both noise and quiet conditions for each participant.

Results

Data Screening. All measures were checked for outliers (i.e., > 3.5 SD) both in terms of intra-individual and interindividual variability. One OA and one ARHL participant were each found to have one extreme score on a cognitive trial and therefore their scores were replaced with the next most extreme value on that trial type for that age group.

Background measures. Descriptive statistics and between-groups analyses are shown for all background measures in Table 1. To examine group differences on the background measures, a series of one-way ANOVAs with follow-up Bonferroni corrected contrasts were performed for measures administered to all three groups of participants. For measures only administered to the older adults (MoCA, DGI), independent samples *t*-tests were conducted to compare the OA and ARHL groups. Notably, compared to the ARHL group, the OA group performed better on processing speed measures (i.e., Coding and DKEFS Trails Condition Three), task switching (DKEFS Trails Condition Four) and the MoCA. Furthermore, the OA group demonstrated higher confidence in both their balance (ABC) and listening (LSEQ) than the ARHL group, and performed better on the objective measure of global mobility (i.e., DGI). However, after controlling for age, OA and ARHL groups only differed significantly on the ABC scale.

Cognitive Accuracy

To assess cognitive performance on the 1-back working memory task, a Group (YA vs. OA vs. ARHL) x Attentional Load (single task vs. dual task) x Auditory Challenge (quiet vs.

noise) mixed factorial ANOVA was performed using the accuracy scores (%; see Figure 1). The analysis revealed a significant main effect of auditory challenge, $F(1, 84) = 413.22$, $p < .001$, $\eta_p^2 = .84$, such that cognitive performance was higher in quiet ($M = 97.79$, $SE = .29$) than noise conditions ($M = 62.21$, $SE = 1.80$). A significant main effect of group was also observed, $F(2, 84) = 3.81$, $p = .026$, $\eta_p^2 = .08$. Pairwise comparisons with Bonferroni correction revealed that YA ($M = 83.61$, $SE = 1.63$) performed significantly better than ARHL ($M = 77.77$, $SE = 1.55$) across all conditions ($p = .033$). All other pairwise comparisons between groups were not statistically significant ($ps \geq .114$). Statistically significant 2-way interactions were observed for group and auditory challenge, $F(2, 84) = 4.82$, $p = .010$, $\eta_p^2 = .10$, and group and attentional load, $F(2, 84) = 5.26$, $p = .007$, $\eta_p^2 = .11$. These were qualified by a significant 3-way interaction of group, auditory challenge and attentional load, $F(2, 84) = 7.30$, $p = .001$, $\eta_p^2 = .15$. This significant 3-way interaction was preserved even when controlling for age and sex, $F(2,81) = 3.21$, $p = .046$, $\eta_p^2 = .073$. All remaining main effects and interactions were not statistically significant ($ps \geq .448$).

To explore the three-way interaction of group, attentional load, and auditory challenge, a series of Attentional Load ANOVAs were performed for each group to investigate the impact of attentional load in noise conditions. Among YA, a main effect of attentional load was observed in noise conditions, $F(1, 28) = 8.77$, $p = .006$, $\eta_p^2 = .24$ such that cognitive accuracy was higher in dual-task noise ($M = 70.96$, $SD = 13.29$) conditions compared with single-task noise conditions ($M = 68.10$, $SD = 14.83$). Among the ARHL group, a main effect of attentional load was also observed in noise conditions, $F(1, 31) = 5.50$, $p = .026$ $\eta_p^2 = .15$ with significantly worse performance in dual-task noise conditions ($M = 55.93$, $SD = 18.99$) compared with single-task noise conditions (*M* = 59.00, *SD* = 19.47). All other main effects were non-significant ($ps \geq$ 0.239).

To further explore dual-tasks costs, a Group x Auditory Challenge ANOVA was performed using 1-back dual-task costs. Analyses revealed a significant main effect of group, which was qualified by a statistically significant 2-way interaction of group and auditory challenge, $F(2, 84) = 7.30$, $p = .001$, $\eta_p^{\,2} = .15$. To explore this interaction, a series of one-way ANOVAs were performed to compare groups on dual-task costs in noise and quiet conditions separately. In noise conditions, there was a statistically significant effect of group on dual-task cost $F(2, 84) = 6.81$, $p = .002$, $\eta^{\,2} = .14$, with Bonferroni corrected pairwise comparisons revealing that ARHL (*M* = 3.07, *SE* = 1.31) demonstrated greater dual-task costs than both YA (*M* = -2.86, *SE* = 0.96) and OA (*M* = -1.67, *SE* = 1.39).

Balance Analysis

Ankle Plantarflexion Amplitude (degrees). A Group x Attentional Load x Auditory Challenge mixed factorial ANOVA was performed using the amplitude of plantarflexion (i.e., foot pointed down) exhibited by the ankles (see Figure 2). Results revealed a main effect of group, $F(2, 81) = 6.60$, $p = .002$, $\eta_p^{\,2} = .140$, with follow-up Bonferroni contrasts indicating that both OA (*M* = -0.90, *SE* = 0.14) and ARHL (*M* = -0.93, *SE* = 0.12) demonstrated greater plantarflexion across all conditions when compared with YA (*M* = -0.35, *SE* = 0.13). The same ANOVA analysis performed using only the two older adult groups and covarying out age and sex revealed non-significant findings ($p_s \geq .151$). Additionally, there was a main effect of attentional load, $F(1, 81) = 11.36$, $p = .001$, $\eta_p^{\,2} = .123$, such that all participants demonstrated greater plantarflexion in single-task (*M* = -0.80, *SE* = 0.08) compared with dual-task (*M* = -0.65, *SE* = 0.07) conditions. To further explore the interference from a secondary cognitive task, dual-task costs (DTC) were calculated by subtracting single-task performance from dual-task performance for both quiet and noisy listening conditions. A Group x Listening Condition ANOVA using DTC as the dependent variable revealed non-significant findings ($p_s \geq 0.196$).

Hip Extension Amplitude (degrees). A Group x Attentional Load x Auditory Challenge mixed factorial ANOVA was performed using amplitude of hip extension (see Figure 2). Analyses revealed an interaction of group and attentional load, $F(2, 81) = 4.38$, $p = .016$, $\eta_p^2 = .098$. Simple main effects analyses were carried out to explore this interaction. Analyses revealed a main effect of attentional load among YA, $F(1, 28) = 5.62$, $p = .025$, $\eta_p^2 = .167$, such that they exhibited more hip extension in dual-task ($M = -0.85$, $SE = 0.16$) compared with single-task ($M = -0.66$, $SE = 0.16$) conditions. All other main effects across age groups were not statistically significant ($ps \geq .062$). The same ANOVA analysis performed using only the two older adult groups and covarying out age and sex revealed non-significant findings ($p_s \geq .054$).

Discussion

The purpose of the current study was to experimentally integrate the two domains of auditory and motor functioning to better understand their correlation, as shown in epidemiological studies (Viljanen et al., 2009). We used a dual-task design to challenge younger adults, older adults, and older adults with age-related hearing loss and evaluated the impact of auditory challenge and cognitive load on dual-task balance performance. As hypothesized, both older adults exhibited disproportionate negative effects with increases in auditory challenge (i.e., noise), and the ARHL group demonstrated greater dual-task costs in noise when compared with OA and YA. Furthermore, in line with the posture first principle, the ARHL group prioritized balance performance over cognitive performance likely due to the ecological value of balancing, whereas YA were able to more flexibly distribute their attentional resources between the auditory task and the balance task.

Auditory Working Memory Performance

The present study was based on the assumption that with age, cognitive resources become more limited and therefore performance might be more negatively impacted by an increased attentional load or when information was presented in a noisy environment. As predicted, the ARHL group demonstrated lower cognitive performance on the 1-back task when compared with YA. Furthermore, all participants were negatively impacted by the addition of noise. Most importantly for our hypothesis and congruent with prior research on the negative impact of babble on word identification and memory encoding (Murphy, Daneman, & Schneider, 2006), this noise effect was magnified among the ARHL group. This finding is notable given that the presentation level of the auditory stimuli was adjusted to correct for individual differences in hearing acuity. In addition, the ARHL group demonstrated a drop in cognitive performance when moving from single- to dual-task conditions in the presence of noise, demonstrating a dual-task cost not present in the other two groups. In contrast, we observed an increase in cognitive performance among YA when moving from single- to dual-task conditions in noise, suggesting an ability to modulate task emphasis as conditions change.

The correlational results further support the cognitive compensation viewpoint (Li & Lindenberger, 2002). Among the ARHL group, 1-back accuracy in the most challenging dual-task noise condition correlated significantly with a measure of working memory ($r = .38$, $p = 0.031$), but not with average hearing thresholds ($r = -.08$, $p = .519$), suggesting that peripheral hearing loss is not enough to account for group differences. Additionally, although the ARHL group demonstrated decreased cognitive abilities on numerous background measures consistent with previous work (e.g., Lin, 2011), controlling for individual differences on background cognitive measures generated the same pattern of findings.

Postural Recovery Strategies

Turning to the parameters reflecting postural recovery, as expected based on previous work (Horak et al., 1997; Nashner & McCollum, 1985), participants implemented more of an ankle strategy in response to less challenging perturbations (i.e., single-task) as compared with more difficult task conditions (i.e., dual-task). Furthermore, congruent with previous research (Brown et al., 1999; Quant et al., 2004), age differences in postural recovery strategy were found. YA exhibited a hip strategy in response to challenging task conditions whereas older adult groups exhibited greater use of an ankle strategy across all conditions, irrespective of hearing status. This finding is further evidence that older adults maintain an attentionally economical strategy to conserve cognitive resources, while younger adults adapt their strategy to increasing task challenge (Brown et al., 1999).

Task Prioritization

Considering the cognitive and balance results together, the current findings also converge with other research (Lajoie et al., 1993) in that YA were able to respond to task manipulations (i.e., addition of noise or concurrent task) and flexibly split attention between the two tasks, whereas older adults maintained a posture first response as a means of protecting balance. Postural prioritization among the ARHL group was further supported through cognitive dual-task costs in noisy conditions, suggesting that they reallocated their cognitive resources to maintaining their postural strategy in the most challenging condition (e.g., Doumas, Smolders, & Krampe, 2008).

These results are in line with the cognitive compensation view (Li & Lindenberger, 2002) in that the ARHL group demonstrated a drop in cognitive performance in the most challenging dual-task noise condition. Importantly, the postural strategy of both older adult groups was invariant in response to the noise manipulation suggesting that the ARHL group reallocated cognitive resources from the working memory to the motor task in order to maintain their posture. Interestingly, the ARHL group also demonstrated a lower score on a self-report measure of balance confidence even after controlling for age, suggesting that their pattern of prioritization may be influenced by a fear of falling. Similar cognitive dual-task costs were not observed for the OA group suggesting they had sufficient cognitive resources to maintain task performance in the most challenging condition. If the level of challenge was increased (e.g., faster perturbation), it is likely that the OA group would also demonstrate a trade-off in performance in favor of maintaining postural stability.

Limitations and Future Directions

One possible limitation to the interpretation of our findings is that we did not control for vestibular dysfunction despite using self-report measures of fall history and vertigo and an objective measure of mobility. However, controlling for vestibular function did not change the magnitude of the association between hearing loss and falls in a study of young adults and older adults (Lin & Ferrucci, 2012). Nevertheless, future studies would benefit from including objective assessment of vestibular impairment (Jacobson & Shepard, 2008). A further limitation is that the sample consisted of older adults with only mild hearing loss (i.e., average pure-tone thresholds of 25-40 dB-A). If older adults with more severe hearing loss were tested in future, we expect that the effect of dual-tasking and noise would be exacerbated among individuals with moderate to severe hearing loss. Lastly, our older adult groups were not balanced for age and sex. However, these demographic variables are strongly correlated with hearing loss (Stenklev & Laukli, 2004) and therefore the current sample of older adult men is representative of the ARHL population. Moreover, group differences on the experimental working memory task were preserved even when controlling for these demographic variables.

Conclusions

The current work complements the epidemiological evidence linking hearing loss and reduced mobility (Viljanen et al., 2009) and provides new experimental evidence showing competition for common cognitive resources in the context of simultaneous auditory and motor demands even after correcting for individual differences in hearing acuity. For older adults with mild hearing loss, this competition for cognitive resources was even more apparent, suggesting that falls risk or reduced working memory efficiency could be exacerbated during everyday activities. Evidence of the interdependence of sensory, motor, and cognitive factors in old age could be used to inform rehabilitation programs in the fields of physical therapy and audiology by incorporating cognitive training (Li et al., 2010). Future research is needed to determine whether cognitive training might therefore reduce the risk of falling particularly in older adults with hearing loss.

Table 1

Means and standard deviations for all baseline measures

Source	*YA*	*OA*	*ARHL*	*Differences*
Age (years)	21.83 (3.01)	65.19 (3.26)	70.75 (5.76)	1, 2, 3
Education (years)	14.15 (1.10)	16.88 (1.66)	16.47 (3.32)	1, 2
Average Hearing Threshold (dB)	11.72 (3.81)	18.48 (3.14)	29.07 (3.78)	1, 2, 3
Letter-Number Sequencing (max 30)	19.66 (2.04)	19.04 (2.81)	18.78 (2.55)	--
Digit Symbol (max 135)	81.54 (8.79)	72.81 (12.78)	61.88 (12.17)	1, 2, 3
DKEFS Trails Condition 2 (seconds)	24.14 (4.43)	32.82 (13.28)	37.37 (12.96)	1, 2
DKEFS Trails Condition 3 (seconds)	26.27 (6.05)	32.20 (10.47)	40.30 (15.49)	2, 3
DKEFS Trails Condition 4 (seconds)	63.24 (21.84)	73.37 (26.73)	102.36 (38.44)	2, 3
DKEFS Trails Difference (seconds)	38.04 (20.05)	42.03 (18.72)	63.53 (32.24)	2, 3
MoCA (max 30)	--	27.88 (1.77)	26.78 (1.93)	3
ABC (max 100)	95.33 (3.24)	96.78 (2.85)	90.68 (9.14)	2, 3
LSEQ (max 100)	89.82 (7.32)	84.42 (9.89)	75.36 (17.04)	2, 3
Sit to Stand (seconds)	10.07 (1.59)	13.09 (3.10)	12.96 (3.57)	1, 2
DGI (max 24)	--	23.73 (0.53)	22.71 (1.74)	3

Note. 1 denotes a statistically significant group difference between YA and OA, 2 denotes a statistically significant group difference between YA and ARHL and 3 denotes a statistically significant group difference between OA and ARHL at $p < .05$. DKEFS = Delis Kaplan Executive Function System. MoCA = Montreal Cognitive Assessment. ABC = Activities-Specific Balance Confidence Scale. LSEQ = Listening Self-Efficacy Questionnaire. DGI = Dynamic Gait Index.

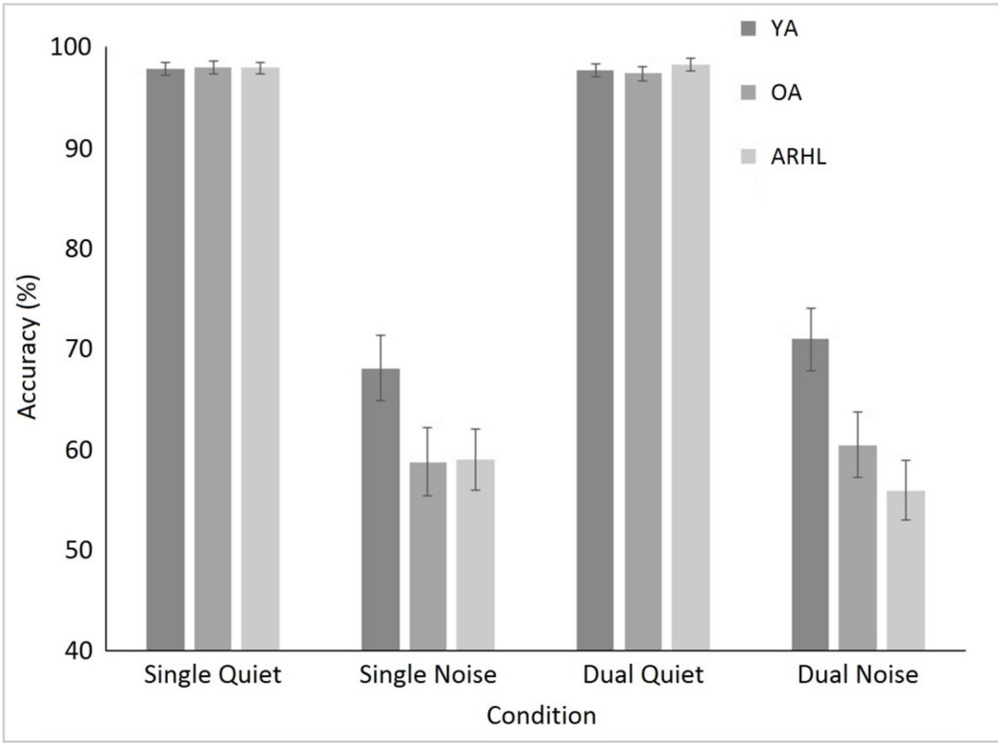

Figure 1. Cognitive 1-back Task Accuracy (%) as a function of age group, auditory challenge, and attentional load. *Note.* Error bars represent one standard error of the mean. YA = younger adults. OA = older adults. ARHL = older adults with age-related hearing loss.

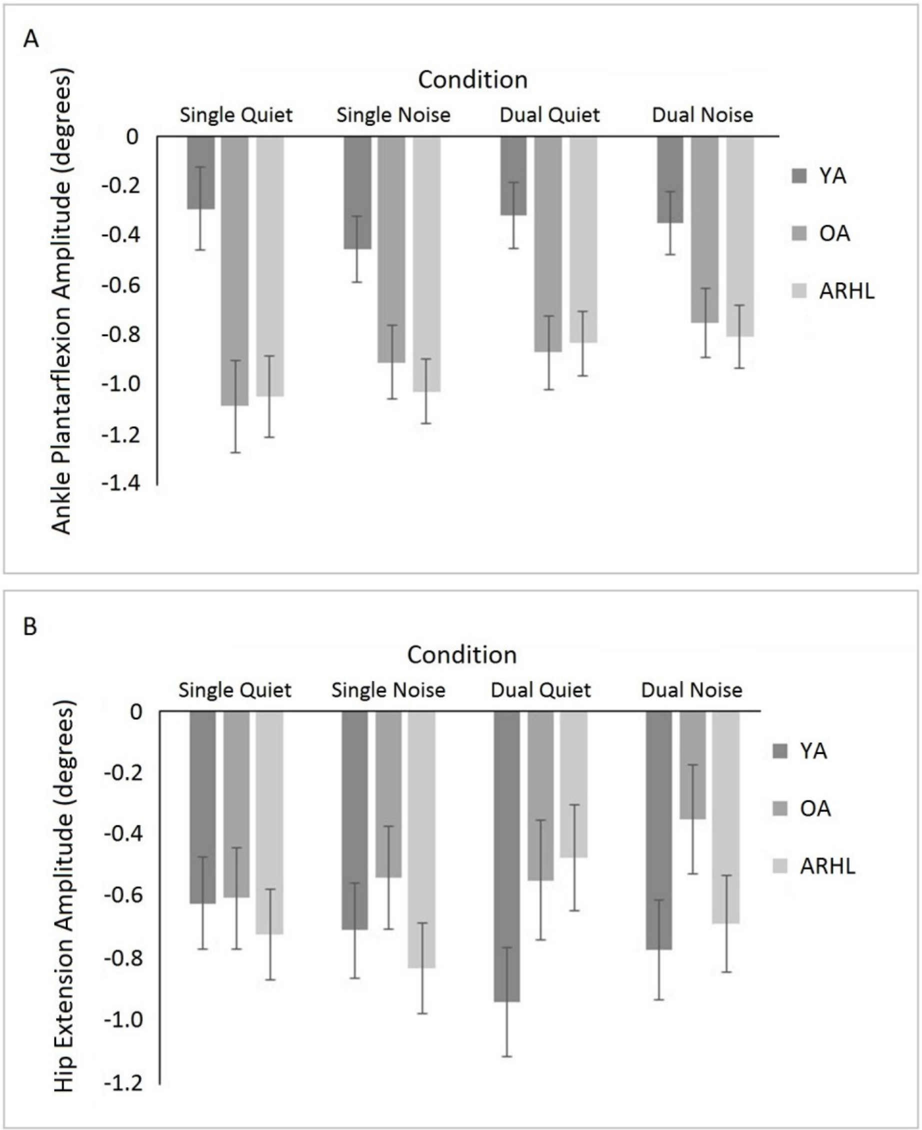

Figure 2. Ankle Plantarflexion Amplitude in degrees (A) and hip extension amplitude in degrees (B) as a function of age group, auditory challenge, and attentional load. *Note.* Error bars represent one standard error of the mean. YA = younger adults. OA = older adults. ARHL = older adults with age-related hearing loss.

CHAPTER THREE

STUDY 2

The Effect of Simultaneously and Sequentially Delivered Cognitive and Aerobic Training on Mobility among Older Adults with Hearing Loss

Abstract

Background: Older adults exhibit declines in auditory and motor functioning, which are compensated for through the recruitment of cognitive resources. Cognitive or physical training alone has been shown to improve cognitive functioning and transfer to motor tasks, but results are mixed when these are combined in studies of healthy older adults, and few studies have included those with age-related hearing loss (ARHL), who are at a higher risk of falls. **Research question:** To examine format effects in mixed training, we used a repeated measures intervention design to compare the efficacy of Simultaneous and Sequential multimodal training formats. **Methods**: 42 older adults (M_{age} = 68.05, SD_{age} = 4.65, females = 26) with (ARHL) and without hearing loss (OAH) completed an intervention study consisting of 12 sessions of multimodal training (computerized cognitive dual-task and recumbent aerobic cycling). Participants were randomly assigned to either the Simultaneous (concurrent cognitive and aerobic) or Sequential training group (cognitive followed by aerobic) and completed assessments of single- and dual-task mobility concurrent with an auditory working memory task. Training gains were assessed with repeated measures ANOVAs using magnitude of improvement from pre- to post-training on primary outcome measures as the dependent variable. **Results**: Gains in auditory working memory were greater in the Sequential group than Simultaneous particularly among OAH. ARHL participants were unaffected by format. While all participants improved on a measure of chair rises, there was no benefit to standing balance. The results demonstrate an advantage to Sequential training, suggesting a benefit to focusing on each task in isolation. **Significance:** The gains noted in the ARHL indicate the potential benefit of incorporating cognitive remediation into traditional audiological rehabilitation. Moreover, it is important to consider the cost of dividing attention when combining training.

Word count: 288 (max 300)

Key words: Motor Aging, Auditory Aging, Balance, Cognitive Compensation

Introduction

Aging is associated with declines in cognitive functioning especially in the domain of executive functions. In tandem, older adults also experience declines in sensorimotor and sensory functioning, which can be compensated for through recruitment of cognitive processes, also termed *Cognitive Compensation* (Li & Lindenberger, 2002). This effect is thought to be exacerbated among older adults with age-related hearing loss (ARHL), who are at a higher risk of falls (Viljanen et al., 2009). There is substantial evidence that cognitive remediation techniques, such as computerized cognitive training (e.g., Li et al., 2010) and exercise (Bherer, Erickson, & Liu-Ambrose, 2013) can enhance cognitive functions and consequently, improve mobility and posture (e.g., Li et al., 2010). More recently, researchers have examined multimodal physical and cognitive training formats in the interest of optimizing training and findings are mixed regarding their cumulative efficacy (Agmon et al., 2014; Zhu et al., 2016). The present study extends this multimodal approach to older adults with mild hearing loss.

Hearing and Motor Aging

There is an increasing interdependence between cognitive and both auditory and motor functioning with age (Li & Lindenberger, 2002). Within the domain of hearing, sensory challenges such as background noise (Pichora-Fuller et al., 2016) and lower signal intensity (Baldwin & Ash, 2011) are more detrimental to older than younger listeners' working memory (WM) performance, and draw upon high-level cognitive processes and executive functions. Executive function involvement has also been observed during balance and walking tasks (Woollacott & Shumway-Cook, 2002). Cognitive-motor dual-task studies demonstrate an age-related increase of cognitive recruitment to perform such tasks (Woollacott & Shumway-Cook, 2002). While a simple cognitive task can sometimes facilitate postural performance (i.e., *U-*

Shaped Non-Linear Interaction Model), dual-task costs are typically observed with increasing task complexity. According to the *Task Prioritization Model,* the nature of these costs depends on the novelty and type of motor task, complexity of the secondary cognitive task and degree of postural reserve and hazard estimation (Wollesen et al., 2017a). When costs are observed in the cognitive domain, this tendency to prioritize posture over the concurrent cognitive task is often referred to as the posture-first principle (Li et al., 2005). We have recently shown that the cost of prioritizing posture is exacerbated among individuals with ARHL, who demonstrate a greater cognitive dual-task cost in challenging balance conditions in in favor of posture (Bruce et al., 2018). Other research has demonstrated that walking parameters are negatively impacted by hearing loss, particularly in dual-task conditions (Wollesen et al., 2017b). Since cognitive capacity is recruited to support performance in both motor and auditory domains, improving cognitive capacity might improve dual-task performance, particularly among ARHL.

Cognitive remediation

Executive function training has been used to address the age-related declines in working memory and executive functions (Lustig, Shah, Seidler, & Reuter-Lorenz, 2009), which are important to target given their involvement in activities of daily living (Loewenstein & Acevedo, 2010). Beyond improving cognition, this type of training produces gains that transfer to motor tasks, with improvements noted in gait speed and balance under dual-task conditions in healthy older adults (Li et al., 2010; Fraser et al., 2017). Another approach to cognitive remediation involves exercise training, with the largest gains observed in measures of executive function and attentional control (Bherer et al., 2013) as well as benefit to gait speed during dual-task walking (Plummer, Zukowski, Giuliani, Hall, & Zurakowski, 2015).

More recently, researchers have implemented multimodal approaches (exercise plus cognitive training) to maximize training gains among healthy older adults (Agmon et al., 2014) as well as with MCI and dementia populations (Karssemeijer et al., 2017) typically using two approaches: Simultaneous training wherein a motor and cognitive task are performed concurrently, and Sequential training wherein the two training modes are performed consecutively. Simultaneous training can be more advantageous as it is more comparable to real-life situations, reduces training time and costs (Theill et al., 2013), and trains coordination between cognitive and physical components (Zhu et al., 2016). However, Simultaneous formats risk taking attention from the cognitive task (Li et al., 2001), while Sequential training allows participants to focus on both cognitive and physical tasks under full attention.

The current literature on the efficacy of multimodal training compared with single domain (cognitive or motor) training is mixed although some have demonstrated transfer to daily activities (Laatar, Kachouri, Borji, Rebai, & Sahli, 2018) and instrumental activities of daily living (Tennstedt & Unverzagt, 2013) using both types of protocols. Some researchers have demonstrated increased efficacy of Sequential (Zhu et al., 2016) and Simultaneous training (Agmon et al., 2014) on dual-task outcome measures with training-related improvements observed through increased performance on the cognitive task, motor task, or on both (Agmon et al., 2014; Wollesen & Voelcker-Rehage, 2013). Using a protocol of tri-weekly training for twelve weeks, others failed to find synergistic benefits from sequentially combined physical and cognitive training (Fraser et al., 2017).

In sum, while many studies using a multimodal training approach have demonstrated an improvement on some aspect of dual-task performance, the heterogeneity of methods makes comparisons between studies challenging (Agmon et al., 2014). To date, no study has directly compared the effects of Sequential and Simultaneous training formats on dual-task mobility outcomes. Additionally, no studies have examined the effect of cognitive remediation on dual-task mobility in older adults with hearing loss (Wollesen et al., 2017b).

Current Study

We aimed to compare the effects of sequential and simultaneous formats of multimodal cognitive and exercise training on cognitive-motor dual-tasking in older adults with and without mild hearing loss. Older adults underwent aerobic exercise training and computerized dual-task training, either sequentially or simultaneously. Given that the efficacy of each training component has been previously established (e.g., Bherer et al., 2013; Fraser et al., 2017), we opted to omit a control group. Single-and dual-task measures of postural control and mobility were assessed and included two levels of listening challenge as primary outcome measures.

Objectives and Hypotheses. Due to the increasing involvement of cognitive resources in hearing with aging, we considered a sub-a of older adults with mild hearing loss and hypothesized that these individuals would demonstrate dual-task training gains on the primary outcome measures, particularly in challenging auditory conditions (e.g., lowered volume). Given the cognitive involvement in sensorimotor and sensory functioning, we also hypothesized that all participants would demonstrate dual-task gains on the primary outcome measures, but based on the literature which shows age-related increases in cognitive-motor DT costs (Woollacott & Shumway-Cook, 2002; Shumway-Cook et al., 1997), the Sequential training group would show larger gains than the Simultaneous group, due to the advantage of training each task under full attention.

Methods

Participants

To achieve a power of .80 at a significance level of $p < .05$ for the group by time interaction, we aimed to test 20 participants per group to allow for attrition. A total of 42 older adults (*M* = 68.05 years, *SD* = 4.65, females = 26) were recruited through a participant pool and newspaper advertisements by the laboratory research staff. Exclusion criteria included the existence of any progressive medical conditions, the use of medications affecting cognition or balance, and suspected presence of mild cognitive impairment as defined by the Montreal Cognitive Assessment (MoCA < 26/30; Nasreddine et al., 2005). Additionally, cardiovascular health was assessed with the Jones protocol (Jones, Makrides, Hitchcock, Chypchar, & McCartney, 1985). Participants were excluded if they presented with cardiac symptoms or an elevated heart rate. All participants were non- hearing aid users. Of a total of 85 participants who were initially recruited, 42 eligible participants were randomly assigned to Simultaneous or Sequential training groups by the research coordinator based on the time at which they were recruited into the study. Participants received an honorarium for their participation. To investigate the impact of hearing status and effortful listening on training gains, participants within each training format were classified by hearing status, resulting in four groups: ARHL Sequential (*n* = 7), ARHL Simultaneous (*n* = 6), OAH Sequential (*n* = 15) and OAH Simultaneous (*n* = 15).

Materials

Screening and background. A health and demographics screening was administered by telephone. Eligible participants underwent in-person tests of sensory, motor, and cognitive functioning. Measures used for screening are marked with an asterisk.

Cognitive measures. Global cognitive functioning was assessed using the Montreal Cognitive Assessment * (Nasreddine et al., 2005). Cognitive processing speed and working memory were assessed using the Coding (Digit Symbol) and Letter Number Sequencing subtests of the Wechsler Adult Intelligence Scale (Wechsler, 2008) respectively. Executive functioning was measured using the Stroop Task (MacLeod, 1991) as an assessment of response inhibition. Scores were derived by dividing the number of correct responses by the total completion time.

Hearing measures. Air-conduction pure-tone audiometry was administered using a Maico (MA 42) audiometer to derive an average pure-tone threshold, which was then used to determine the appropriate intensity at which to present the auditory experimental stimuli. Participants were presented with pure tones at varying frequencies (250-8000 Hz) following standard procedure, from which average detection thresholds were derived (500, 1000, 2000 and 3000 Hz) averaged across both ears. Participants were classified as having normal hearing: OAH with average pure-tone hearing thresholds below 25 dB HL (decibel hearing level), or with mild hearing loss: ARHL, with average pure-tone hearing thresholds between 25-40 dB HL. Subjective hearing was assessed using the Listening Self Efficacy Questionnaire (LSEQ; Smith et al., 2011).

Physical measures. The Activities-Specific Balance Confidence Scale "ABC Scale" (Powell & Myers, 1995) assessed self-reported balance confidence. The Jones Test (Jones et al., 1985)* was performed on a stationary bike, as a sub-maximal estimate of maximum heart rate.

Training Tasks.

Dual-task (DT) Training. The DT training task (Lussier, Gagnon, & Bherer, 2016) was adapted for iPad use (MD785CL/BIOS 8.2) and is described elsewhere (Lussier et al., 2016; Lai, Bruce, Bherer, Lussier, & Li, 2017). Each of the two tasks involved the presentation of a central figure (e.g., fruits, vehicles), to which participants responded by pressing the corresponding button (see Appendix B). Response times and errors were recorded (Lai et al., 2017). Blocks of single- and dual-task trials were given, with individualized and continuous feedback. Each session lasted approximately 30 minutes.

Physical Training. The aerobic training component involved recumbent cycling, chosen to minimize balance demands. Physical workload was increased from 40% of baseline estimated maximum heart rate in Sessions 1-4, to 44% in Sessions 5-8, and to 48% in Sessions 9-12. Each training session lasted 35 minutes (5 min. warm-up, 25 min. at target heart rate, 5 min. cool-down).

Outcome measures.

Four different motor tasks were performed singly (A) and concurrently (B) with a cognitive task described below under both low and ideal conditions. Participants completed two trials of each condition in an ABBA format.

Sit-to-stand task. The Sit-to-Stand task (Puthoff, 2008) served as a measure of global mobility, as indexed by the total time to complete five chair rises with arms crossed.

Balance task. Balance was assessed using a NeuroCom Equitest apparatus (computerized dynamic posturography). Participants completed three balancing conditions: double support, visual sway-referenced (i.e., visual surround moves synchronously with sway in AP dimension), and single-support (i.e., balancing on their preferred leg). Each trial was 30 seconds and the outcome measure was the ellipse area (mm^2).

Cognitive task. The auditory working memory "*n*-back" task (Kirchner, 1958) served as the cognitive outcome measure. In each trial, participants were presented with fifteen pseudo-randomly ordered (without consecutive repetition) single digit numbers between one and ten excluding the two-syllable numeral seven. The stimuli were presented via insert headphones (E-A-RLINK 3A) at 35 dB HL above each participant's average pure-tone threshold. Participants were asked to report the number presented one item prior to the currently presented number (1-back). To increase auditory challenge, half the trials were presented more quietly (i.e., 20 dB HL above the average pure-tone threshold; 12). The number of correct responses was averaged across trials in each condition.

Procedure

Participants underwent two pre-assessment sessions. First, they were administered the neuropsychological measures. In Session 2, they underwent the physical assessment (blood pressure, height, weight, heart rate, and sub-maximal VO_2) and baseline testing on the *n*-back task. As well, the experimental tests of single- and dual-task auditory working memory and balance were given. Three short warning beeps preceded each trial, and one short beep signaled the end of each trial. The experimental procedure was performed under both ideal and low listening conditions, in counterbalanced order.

Training was administered in blocks of four to seven people who met twice per week for six weeks, for a total of 12 sessions and once one cohort had completed training, a new one started. The Simultaneous training groups performed both training tasks at the same time (30 minutes total), while the Sequential training group first performed the iPad training task (30 minutes) followed by recumbent cycling (30 minutes) to equate the "dosage" of each training activity across groups. Following the final training session, both groups completed identical post-training assessments. Personnel involved in training were different from those conducting pre- and post-training assessments to remain blind to treatment condition. There was no attrition such that all participants randomized to treatments completed the training protocols.

Planned Analyses. Analysis of the primary outcome measures was performed using repeated measures mixed factorial ANOVAs. Where appropriate, multiple tests were Bonferonni corrected and otherwise, results were considered significant at $p < .05$.

Results

Data screening. All background and baseline experimental measures were checked for outliers (i.e., > 3.5 SD) both in terms of intra-individual and interindividual variability and extreme scores were winsorized. Additionally, a square root transformation was applied to two scores which demonstrated non-normal distributions: changes scores on the n-back task in dual ideal single-support conditions (skew = 3.91, kurtosis = 20.02) and on the Neurocom data for the single-task single support condition (skew = -3.19, kurtosis = 15.80). Data from one participant were removed due to extreme posture scores, leaving 21 participants in the Simultaneous group and 20 participants in the Sequential group. For the analysis of single-support performance, data from six participants were excluded due to difficulty performing the task correctly, leaving data from 18 participants in the Simultaneous group and 17 participants in the Sequential group.

Baseline assessment. Descriptive statistics and between-groups analyses are shown for all background measures and baseline experimental measures in Table 1. A series of one-way ANOVAs with Bonferroni corrected contrasts were conducted to compare the four training groups at baseline, confirming that beyond differences in PTA between the two hearing groups such that both ARHL groups had worse hearing than both OAH groups, the groups did not differ significantly on any other background measures ($p_s \geq 0.103$) or baseline experimental measures ($p_s \geq 0.209$).

Dual-task training. To confirm that the dual-task training was effective, changes in iPad dual-task reaction times and error rates were analyzed across early, middle and late phases of training pooling all participants (*n* = 41). The analysis revealed a significant main effect of time for reaction times, $F(2, 42) = 91.76$, p = <.001, $\eta_p^{\,2} = 0.814$, 95% CI [0.69, 0.86], and error rates, $F(2,76) = 14.63$ p < .001, $\eta_p^{\,2} = 0.28$, 95% CI [0.11, 0.41]. Bonferroni corrected contrasts revealed that reaction times and error rates improved post training ($p_s < .001$), replicating previous work [35].

Change scores. Change scores for all primary outcomes were calculated by subtracting baseline scores from post-training scores.

Cognitive task. To assess training related effects in the cognitive domain, a Group (ARHL Sequential vs. ARHL Simultaneous vs. OAH Sequential vs. OAH Simultaneous) x Balance (seated vs. STS vs. double support vs. visual vs. single support) x Listening Level (ideal vs. low) mixed factorial ANOVA was performed using change scores on the *n*-back task (Figure 1, Table 2 for significant pre-post changes). A main effect of balance was observed, $F(4, 116) = 3.64$, $p = 0.008$ $\eta_p^{\,2} = 0.11$, 95% CI [0.01, 0.20], with follow-up Bonferroni contrasts indicating greater gains in stable ($M = 0.76$, $SE = 0.45$) and visual ($M = 0.83$, $SE = 0.44$) conditions compared with single support ($M = 0.00$, $SE = 0.47$). The main effect of group, $F(3, 29) = 5.04$, $p = 0.006$, $\eta_p^{\,2} = 0.34$, 95% CI [0.04, 0.51], was also significant, and was qualified by a significant interaction between group and listening level, $F(3, 29) = 4.15$, $p = 0.015$, $\eta_p^{\,2} = 0.30$, 95% CI [0.01, 0.47]. A series of one-way ANOVAs were performed to compare groups on *n*-back change scores separately for low and ideal listening conditions. In low conditions, there was a statistically significant effect of group on training gains, $F(3,32) = 221.88$, $p = .008$. Bonferroni corrected contrasts revealed greater gains in the Sequential OAH group ($M = 4.08$, $SE = 1.25$) compared with the Simultaneous OAH group ($M = -2.01$, $SE = 1.06$), $p = .005$. All other group contrasts were non-significant ($p \geq 0.554$) and a similar pattern was not observed in ideal conditions (p = 0.170). Numerically, it appeared that the ARHL group improved post training regardless of format.

Sit-to-Stand. A Group (4) x Challenge (Single vs. Dual-Ideal vs. Dual-Low) mixed factorial ANOVA was performed using change scores in timed performance (Figure 2, Table 2 for significant pre-post changes). A significant main effect of challenge was observed, $F(2, 74)$ = 4.29, p = 0.017, $\eta_p{}^2$ = .0.10, 95% CI [0.01, 0.23], with Bonferroni corrected comparisons revealing greater reductions of time in Dual-Ideal (M = -0.91, SE = 0.40), p = .028 and Dual-Low (M = -1.14, SE = 0.55), p = .021 conditions compared with Single-Task conditions (M = -0.037, SE = 0.30).

Standing balance. To assess change on the Equitest task, a Group x Balance (stable vs. visual vs. single support) x Challenge (Single vs. Dual-Ideal vs. Dual-Low) mixed factorial ANOVA was performed using change scores in ellipse area (Figure 3, Table 3). The analysis revealed non-significant findings ($p \geq 0.415$).

Discussion

The purpose of the current study was to compare the effects of Sequential and Simultaneous formats of cognitive (i.e., computerized dual-task) and exercise (i.e., aerobic) training on the primary outcome measures of cognitive-motor dual-tasking (n-back, sit-to-stand, balance task).

Auditory Working Memory Gains

As hypothesized, sequentially trained participants demonstrated significant gains on the auditory working memory task under dual-task conditions. In contrast, the Simultaneous group did not demonstrate similar gains, suggesting a cost associated with dividing attention during training. Support for this interpretation is found in the cognitive training data, in which the

Sequential group outperformed the Simultaneous group, if only numerically (Lai et al., 2017). By contrast, group equivalence was observed on both subjective (Borg Scale; p = .509) and objective (i.e., mean power output in Watts; p = .833) measures of physical workload. This overall pattern is consistent with a postural prioritization strategy (Li et al., 2005), in that the cost of dividing attention during training was observed on the cognitive rather than the physical task. This pattern was likely influenced by the complexity of the cognitive training task (i.e., *U-Shaped Non-Linear Interaction Model)*. Moreover, according to the *Task Prioritization Model,* other factors which were not explicitly measured such as the novelty of the physical training task and low postural reserve may also have contributed to these findings (Wollesen et al., 2017a). The Sequential training group also demonstrated larger gains on an independent measure of working memory (LNS) than the Simultaneous group (Lai et al., 2017).

As anticipated, hearing status interacted with group format to influence training gains. The ARHL participants appeared numerically to benefit from training regardless of training format. These gains were most apparent in the low volume listening conditions, which has been shown as detrimental to older adult's auditory WM performance (Baldwin & Ash, 2011). Pairing a challenging auditory and motor task exacerbated these costs (Bruce et al., 2017). Strengthening cognitive resources through training may have enabled these participants to better compensate for age-related sensory loss.

Motor Outcome Measures

In line with previous work, both groups demonstrated improved performance on sit-to-stand performance under dual-task conditions (Desjardins-Crépeau et al., 2016; Strouwen et al., 2017); however, no pre-post improvements were observed for the measures of balance. These findings may be explained using the concept of postural prioritization. Specifically, if older adults were prioritizing posture throughout the assessment sessions, the cognitive training might have freed up capacity for the lower priority task, namely WM. This pattern echoes previous work on balance and walking, in which training reduced brain activation during imagined motor tasks, freeing resources up for secondary cognitive tasks (Godde & Voelcker-Rehage, 2017).

Limitations and Future Directions

A limitation of the current study is that our sample consisted of healthy older adults and individuals with only mild hearing loss. A second limitation was the administration of cognitive training before exercise in the Sequential group, which was done to enable participants to quickly transition from cognitive to exercise training (Barban et al., 2017). Another issue is the absence of ecological measures of dual-task gait or balance which could provide information regarding the transferability of training to everyday functioning. Additionally, future studies could sample older adults with more severe hearing loss or fallers who rely more heavily on cognitive resources to compensate for sensory/sensorimotor decline. A final limitation is the use of moderate intensity for our aerobic training which may have limited training related gains. However, previous research in simultaneous training demonstrated that increasing physical training beyond moderate levels negatively impacted performance on the concurrent secondary task (Labelle, Bosquet, Mekary, & Bherer, 2013).

Conclusions

The current work complements the existing multimodal training literature and provides new experimental evidence on how to optimize training, particularly for those with age-related hearing loss. When combining cognitive and physical training, it is important to consider the cost of dividing attention, which may detract from performance gains. Moreover, to date, traditional audiological rehabilitation focuses on amplification, environmental support and formal listening training. The current study suggests that cognitive training may be beneficial to this population particularly in the context of complex listening conditions, such as listening while balancing.

Table 1.

Means and standard deviations for all baseline background and experimental measures

Source	*Simultaneous*	*Sequential*	*p value*
Age (years)	68.19 (4.66)	68.60 (5.26)	0.793
Education (years)	16.76 (2.84)	16.22 (2.82)	0.557
Vo2 Max (220-age)	37.77 (5.87)	36.05 (9.36)	0.488
Mean Power (Watts)	50.86 (15.94)	46.50 (13.88)	0.357
Average Hearing Threshold (dB) pooled	22.38 (6.55)	20.00 (8.24)	0.311
Healthy Older Adults	19.44 (4.72)	15.90 (7.25)	0.132
Older Adults with Age-Related Hearing Loss	29.72 (4.34)	27.62 (2.37)	0.291
Montreal Cognitive Assessment (max. 30)	27.29 (1.68)	27.80 (1.64)	0.328
Letter-Number Sequencing (max. 30)	19.29 (2.00)	18.70 (2.36)	0.397
Digit Symbol (max. 135)	66.57 (14.62)	64.25 (11.93)	0.582
Stroop Colour Naming (# correct / second)	1.28 (0.32)	1.20 (0.30)	0.420
Stroop Word Reading (# correct / second)	0.86 (0.21)	0.77 (0.14)	0.122
Balance Confidence (max. 100)	95.29 (5.55)	95.07 (5.44)	0.900
Listening Self-Efficacy (max. 100)	83.02 (12.54)	86.64 (9.43)	0.312
Sit-to-Stand (seconds)	9.84 (2.55)	10.74 (2.80)	0.289

N-back Ideal (# correct)	13.76 (0.89)	12.80 (1.96)	0.055
Double Support (mm^2)	163.72 (227.41)	167.43 (220.32)	0.538

Note. * denotes a statistically significant group difference at p <.05.

Table 2.

Mean performance on the aerobic training task, n-back and Sit-to-Stand tasks

Condition	Sequential		Simultaneous	
	Pre	Post	Pre	Post
Power (Watts)	44.13(18.28)	42.25(11.78)	56.02(16.71)	49.95(15.07)
		N-back task (# correct)		
Single-ideal	12.80 (1.96)	13.40 (1.43)	13.76 (0.89)	13.86 (0.36)
Single-low	9.20 (3.46)	12.15 (3.40)*	11.10 (3.58)	11.00 (4.14)
Dual-STS-ideal	11.95 (2.08)	13.28 (1.53)*	12.88 (1.07)	12.81 (1.34)
Dual-STS-low	6.88 (4.21)	10.22 (3.21)*	8.24 (3.92)	8.31 (4.24)
Dual-DS-ideal	13.40 (1.22)	13.85(0.56)*	13.62 (0.65)	13.90 (0.26)*
Dual-DS-low	8.73 (4.37)	11.48 (3.34)*	10.57 (4.14)	10.07 (4.54)
Dual-visual-ideal	13.58 (1.04)	13.60 (0.62)	13.81 (0.49)	13.83 (0.46)
Dual-visual-low	9.00 (4.33)	11.28 (3.10)*	10.07 (4.12)	10.50 (4.33)
Dual-SS-ideal	13.50 (1.55)	13.63 (0.62)	13.94 (0.24)	13.89 (0.32)
Dual-SS-low	9.75 (3.94)	11.87 (2.70)	11.72 (3.87)	9.72 (4.78)
		Sit-to-Stand (seconds)		
Single	10.74 (2.80)	10.61 (3.34)	9.83 (2.55)	9.76 (2.59)
Dual-ideal	13.17 (3.29)	11.85 (3.19)*	11.29 (2.42)	10.75 (2.31)
Dual-low	13.83 (4.19)	12.20 (3.41)	12.08 (2.42)	11.11 (2.93)

Note. STS = Sit-to-Stand. DS = double support. * denotes a statistically significant change from pre to post at $p < .05$.

Table 3.

Mean performance on the standing balance tasks (mm^2)

Condition	Sequential		Simultaneous	
	Pre	Post	Pre	Post
Single-double support	167.43	202.00	163.72	125.60
	(220.32)	(256.88)	(227.41)	(154.99)
Dual-double support-ideal	96.59	166.07	138.21	134.63
	(72.32)	(240.12)	(186.65)	(167.35)
Dual-double support-low	227.57	133.16	103.76	120.46
	(378.07)	(133.78)	(156.31)	(89.11)
Single-visual	442.72	296.91	208.93	155.76
	(797.51)	(326.28)	(228.65)	(113.96)
Dual-visual-ideal	175.36	242.99	159.96	139.67
	(149.07)	(309.26)	(141.71)	(107.98)
Dual-visual-low	225.62	262.13	177.70	113.75
	(268.43)	(293.29)	(225.38)	(69.57)
Single-single support	2240.95	908.40	969.28	1056.82
	(4770.86)	(908.98)	(1622.88)	(1379.00)
Dual-single support-ideal	887.06	710.77	572.89	835.17
	(977.53)	(636.58)	(486.92)	(738.61)
Dual-single support-low	1142.05	726.51	910.02	550.50
	(1980.11)	(955.91)	(1638.60)	(288.07)

Note. * denotes a statistically significant change from pre to post at $p < .05$.

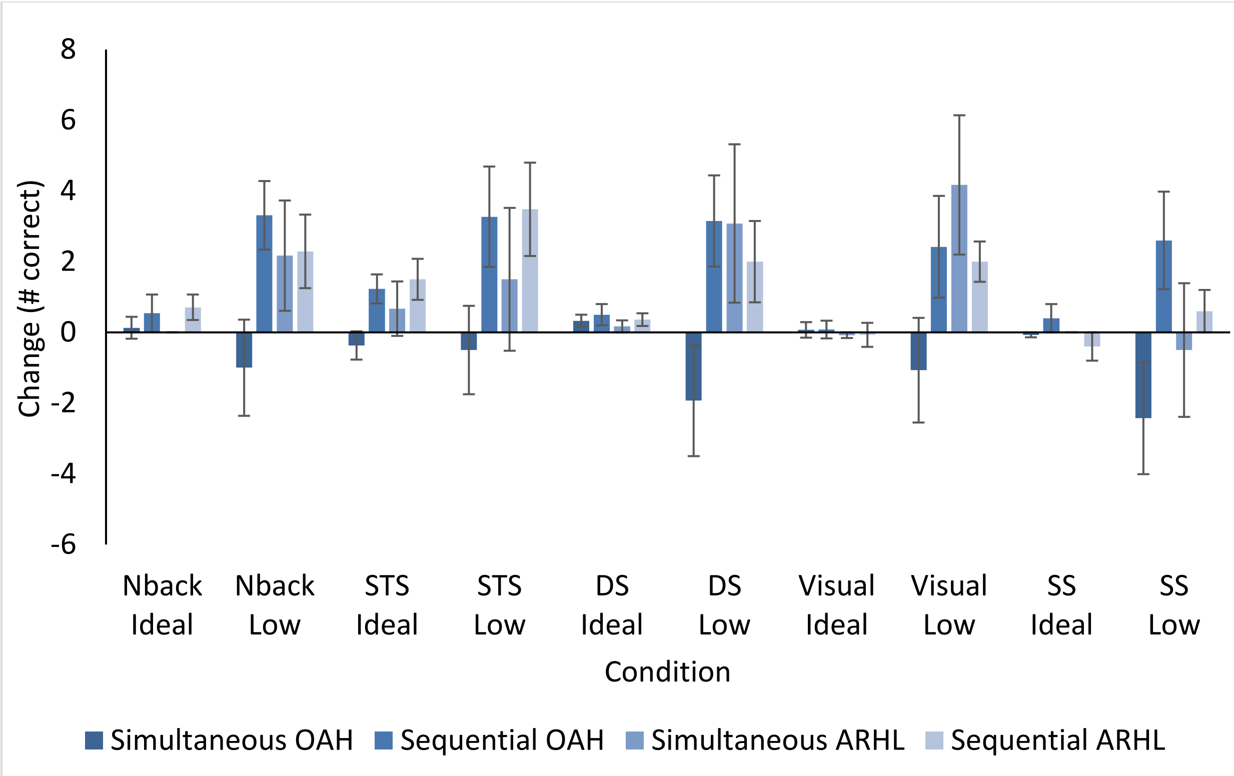

Figure 1. Change scores for the *n*-back task performed during the standing balance tasks and the STS divided by four groups. *Note.* Error bars represent one standard error of the mean. STS=Sit-to-Stand. DS = Double Support. Visual = Visual sway-referenced. SS=Single Support.

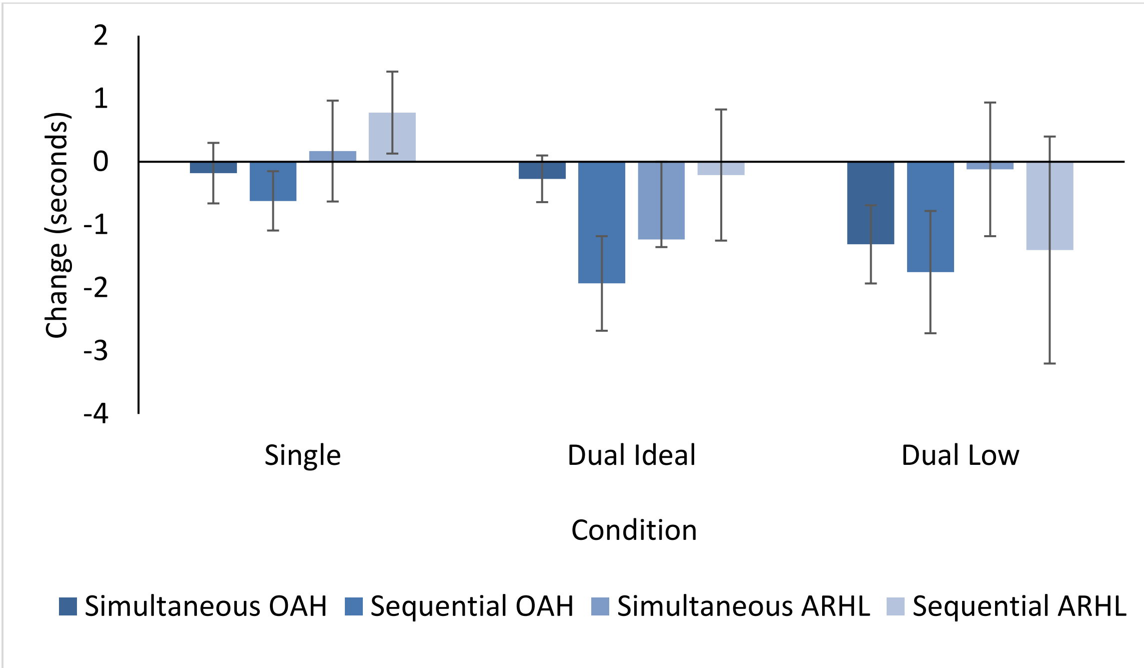

Figure 2. Change scores for the Sit-to-Stand Task. *Note.* Negative values indicate a reduction in completion time and improvement in performance. Error bars represent one standard error of the mean.

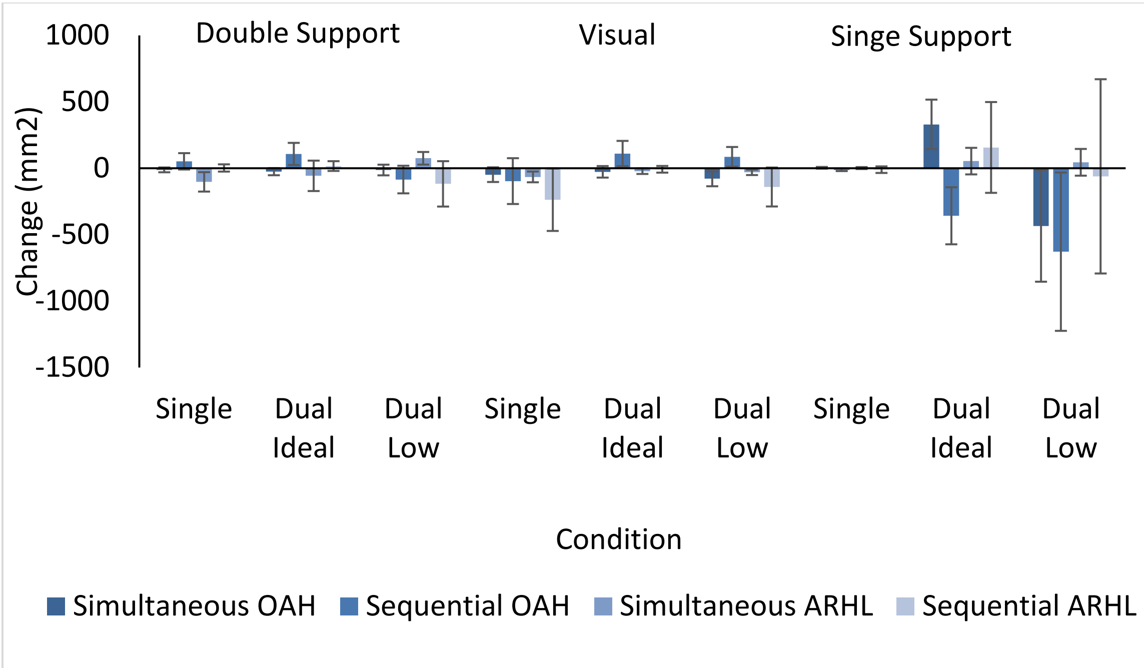

Figure 3. Change scores for the standing balance tasks (ellipse area). *Note.* Error bars represent one standard error of the mean. DS = Double Support. SS=Single Support.

CHAPTER FOUR

STUDY 3

The Role of Cognition in Hearing Loss and Mobility among Older Adults with Age-Related Hearing Loss

Abstract

Background: Epidemiological research indicates a link between hearing loss and poor mobility in older adults (Viljanen et al., 2009). Moreover, cognitive resources and everyday functioning are more strongly related in older adults with sensory impairments than in unimpaired controls (Heyl & Wahl, 2012). A potential explanation is that because both sensory and motor aging are associated with cognitive compensation, these domains compete for common cognitive capacity (Bruce et al., 2017). However, the interrelationships among cognitive, sensory, and motoric abilities are not often considered together, nor are subjective and objective measures commonly compared. **Methods:** The study consisted of a combined dataset of healthy older adults ($N = 218$; $M_{age} = 69.11$, $SD_{age} = 5.89$,) with normal hearing and with age-related hearing loss, as defined using standard audiometric cut-offs (average pure-tone threshold ≥ 25 dB HL at 500, 1000, 2000 Hz in the better ear). All participants completed standardized cognitive tests (MoCA, Letter-Number Sequencing, Digit Symbol Coding), as well as objective and subjective assessments of hearing (pure-tone testing, Listening Self-Efficacy Questionnaire) and mobility (Dynamic Gait Index, Activities-specific Balance Confidence Scale). **Results:** Confirmatory factor analysis first determined that these assessment measures loaded on the relevant latent constructs: hearing, mobility and cognition. These latent constructs were then used to perform subsequent structural equation modeling (SEM) analyses. A negative association was found between hearing and both mobility and cognitive functioning, such that greater hearing loss predicted lower scores on measures of mobility and cognition. Subdividing the sample by objective and self-efficacy measures revealed that the association between lower objective hearing loss and greater mobility was mediated through higher cognitive performance. Turning to the self-efficacy measures, lower listening self-efficacy was associated with lower balance confidence. **Conclusions:**

Together, these results suggest that hearing loss affects both mobility and cognition, and that subjective measures may be useful in assessing perceived effort in these domains. Moreover, individuals with poor hearing appear to rely more heavily on cognitive capacity when performing an objective mobility task.

Introduction

Older adults with hearing loss are at a higher risk for falls (Viljanen et al., 2009) even when controlling for objectively assessed vestibular dysfunction (Lin & Ferruci, 2012). While there are several hypothesized links for this association, one explanation is that of cognitive compensation (Li & Lindenberger, 2002), wherein older adults compensate for declining sensorimotor and sensory functioning through the recruitment of cognitive processes. To date, correlational and experimental work has demonstrated the increased involvement of cognitive resources in both listening and motor functioning among older adults (e.g., Agmon et al., 2016; Pichora-Fuller et al., 2016; Yogev-Seligman et al., 2008). Other researchers (Heyl & Wahl, 2012) have shown that the relation between cognitive abilities and everyday behaviors such as activities of daily living (e.g. using public transport), is stronger in populations with sensory loss compared with healthy controls. One explanation is that the relation between cognition and mobility increases in those with sensory impairment and is reflected in assessments of everyday functioning. To date, few studies have considered hearing, motor and cognitive functioning together using both self-efficacy and objective assessments of mobility and hearing loss.

Hearing Loss and Falls

Epidemiologic studies have revealed that older adults with hearing loss are at a higher risk for falls (Viljanen et al., 2009), even when accounting for vestibular function (Lin & Ferruci, 2012). Experimental research suggests that self-reported hearing loss is associated with slowed walking speed (Tomioka et al., 2015), as well as reduced mobility and day-to-day functioning (Gispen, Chen, Genther, & Lin, 2014). Other studies have implemented objective assessments of hearing using pure tone audiometry to demonstrate that hearing impairment is independently associated with poorer objective physical functioning in older adults, as well as an increased risk for incident disability (Chen et al., 2015). One explanation for this association is that older adults use higher-level cognitive processes (i.e., cognitive compensation) to compensate for declines in sensorimotor and sensory functioning (Li & Lindenberger, 2002). Specifically hearing loss may result in a greater amount of cognitive resources being applied to listening at the expense of safe motor function. However, testing this hypothesis requires an assessment of motor, sensory, and cognitive functions within the same individuals.

Cognitive Compensation in Sensory and Sensorimotor Functioning.

Beyond peripheral changes, both sensory and sensorimotor functioning increasingly rely on cognitive resources with age (Li & Lindenberger, 2002). To this end, researchers have demonstrated stronger relations between sensory loss and cognition in older, compared to middle-aged and young adults (Baltes & Lindenberger, 1997; Lindenberger & Ghisletta, 2008). Moreover, hearing loss has been linked to incident cognitive decline even when controlling for known confounders, and, greater hearing loss, as assessed by objective audiometric testing, is associated with lower scores on both verbal and nonverbal cognitive tests of processing speed, executive function, memory, and global cognition (Bush, Lister, Lin, Betz, & Edwards, 2015; Lin et al., 2011). Other evidence comes from dual-task studies, wherein older adults demonstrate greater cognitive dual-task costs than younger adults on a secondary cognitive task when performing a concurrent listening task (e.g., Gosselin & Gagné, 2012; Tun et al., 2009).

Similarly, the involvement of cognitive resources in mobility and posture has been demonstrated in correlational work, which suggests that lower performance on measures of executive function is associated with greater stride time variability and slowed gait speed (Beauchet et al., 2012; Demnitz et al., 2016; Yogev-Seligmann et al., 2008) as well as self-reported incidence of recurrent falls (Anstey et al., 2009). In keeping with the work on auditory aging, experimental approaches using dual-task paradigms have revealed dual-task costs among older adults when performing concurrent cognitive and posture tasks (Brown et al., 1999; Norrie, Maki, Staines, & McIllroy, 2002). Notably, these costs are typically most evident in the cognitive domain as older adults tend to prioritize posture over cognitive performance, termed postural prioritization (Li et al., 2005). Moreover, older adults with mild hearing loss show greater dual-task costs when performing a concurrent auditory and balance task, and computerized cognitive training is beneficial to this population particularly in challenging dual-task conditions (Bruce et al., 2017; Bruce et al., 2018). Similarly, using virtual-reality to mimic everyday sensory-motor challenges, all older adults appeared to prioritize safe walking, although those with hearing loss generally demonstrated lower performance on the auditory cognitive task and greater stride time variability (Lau et al., 2016; Nieborowska et al, in press).

Sensory Impairment and Everyday Functioning

Moving from the laboratory to everyday functioning, Heyl and Wahl (2012) used structural equation modeling techniques to investigate the relation between sensory impairment classified using clinical assessment tools (e.g., pure-tone audiometry, hearing aid use), objective measures of cognition (e.g., processing speed, working memory), behavior-related everyday functioning (i.e., Activities of Daily Living; ADLs, instrumental ADLs; iADLs) and self-reported mastery of everyday activities and the environment (Ryff, 1989; e.g., I have been able to build a home and a lifestyle for myself that is much to my liking). Using these variables, they demonstrated that cognitive resources and everyday functioning are more strongly related in older adults with visual and hearing impairment(s), compared with healthy controls. Moreover, sensory impaired older adults were more aware of subtle cognitive changes as suggested by stronger associations between cognitive functioning and individuals’ evaluation of everyday functioning as measured by their feelings of subjective autonomy and feelings of mastery and competency in managing the environment. This increased sensitivity was associated with decreased confidence in mastering day-to-day life (Heyl & Wahl, 2012). Although mobility was not formally assessed, one possibility is that their results may, in part, reflect the effects of cognitive capacity and physical status on mobility. Moreover, although the study included both subjective and objective assessments of everyday functioning, self-efficacy in the hearing and mobility domains were not assessed and could be important given that older adults with hearing loss report effortful listening (Pichora-Fuller et al., 2016) and that balance confidence is linked to avoidance of daily activities (Rand et al., 2011).

Self-Efficacy and Aging

Self-efficacy can be defined as an individuals' perceptions of their abilities in specific domains which will determine whether they engage in particular activities (Bandura, 1997). This concept is important in the context of aging because in combination with age-related decline, negative stereotypes of aging may be one of the reasons why self-perceptions of abilities of function do not always accurately represent their actual abilities (Chasteen et al., 2015). Within the domain of hearing, listening self-efficacy may be more related to perceived difficulty in given situations and hearing handicap rather than performance on clinical objective measures (Smith et al., 2011). Moreover, hearing impairment is associated with self-perceived social engagement restrictions (Gopinath et al., 2012) as well as reduced functioning in daily life, self-reported hearing handicap and communication difficulties (Dalton et al., 2003). Similarly, within the motor domain, objective balance performance is a strong determinant of balance confidence, but cannot fully account for all the variance in balance confidence (Hatch et al., 2003) and this low confidence can lead to avoidance of activities resulting in physical frailty, falls and loss of independence (Rand et al., 2011).

Current Study

In sum, previous work has investigated the involvement of cognitive resources in hearing and mobility largely separately, with some emerging experimental and correlational work considering these domains together (Agmon et al., 2017; Bruce et al., 2017; Bruce et al., 2018; Lau et al., 2016; Nieborowska et al, in press; Wollesen et al., 2017b). However, the interrelationships among cognitive, sensory, and motoric abilities are not often considered together, nor are self-efficacy and objective assessments of sensory and motoric ability commonly compared. Therefore, the goal of this study was to use structural equation modeling to examine the relationship between measures of hearing loss and mobility, and whether this association is influenced by cognitive status. We predicted that increased hearing loss would be associated with lower mobility and that this association would be mediated through cognition. This hypothesis was investigated by considering a pooled sample of older adults from two independent studies (Bruce et al., 2017; Bruce et al., 2018), as well as by subdividing the data by type of measure used (i.e., objective or subjective). Within these subdivided models, we further predicted that self-efficacy would be an important contributor to understanding the association between these measures, given that persons with sensory impairment generally report less mastery of their environment and daily activities which likely include demands on hearing and mobility.

Method

Participants

A total of 218 participants (M_{age} = 69.11, SD_{age} = 5.89, females = 127) were pooled across two experimental studies of aging, hearing loss, mobility, and cognition (Bruce et al., 2017; Bruce et al., 2018; Lai et al., 2017), which included both normal hearing older adults as well as older adults with mild hearing loss (35.5%), defined as a pure-tone threshold of 25-40 dB HL at octave test frequencies below 4kHz in the better ear (see Table 1). For both studies, participants were recruited through an existing senior participant pool at Concordia and advertisements in a local senior newspaper. They received an honorarium for their participation ($20 - $300 depending on the length of each study). Using standard audiometric testing, the mean absolute threshold of hearing (i.e., Pure Tone Audiometry; PTA) was calculated using the average of the minimum tone detection thresholds assessed across test frequencies of 500, 1000, 2000 and 3000 Hz from the better ear. To maximize the range of scores, the average PTA spanned from mild to profound hearing loss. Similarly, for the Montreal Cognitive Assessment (MoCA), we included participants with scores below the cutoff of 26 as a means of maximizing the range of scores (range: 17-30). All participants were screened for the existence of any progressive medical conditions and self-reported mobility or vestibular difficulties and had normal or corrected-to-normal visual acuity.

Materials

Cognitive measures. Global cognitive functioning was assessed using the Montreal Cognitive Assessment "MoCA" (Nasreddine et al., 1996) with a score of 26/30 or greater indicating normal cognitive performance. Cognitive processing speed and working memory were assessed using the Coding (Digit Symbol) Task (Wechsler, 2008) and Letter Number Sequencing (Wechsler, 2008) subtests of the Wechsler Adult Intelligence Scale (WAIS-IV; Wechsler, 2008), respectively.

Sensory measures. Pure-tone audiometry was administered using a Maico (MA 42) audiometer to assess participants' hearing acuity for group classification, and to derive an average pure-tone threshold. Participants were presented with pure tones at varying frequencies (250, 500, 2000, 3000, 4000, and 8000 Hz) and intensities over headphones and indicated that a tone was detected by pressing a hand-held button. Participants were also administered the Listening Self Efficacy Questionnaire (LSEQ: Smith et al., 2011), as a subjective index of hearing ability. Participants were asked to rate their level of confidence on a scale of 0 (i.e., cannot do this at all) to 100 (i.e., I am certain I can do this) in a variety of listening conditions (e.g., I can understand the TV, I can understand conversation when someone speaks in a whisper) without the use of listening aids. A summary score was derived by averaging responses across the eighteen items.

Physical measures. Global mobility was assessed using the Dynamic Gait Index (DGI: Shumway-Cook et al., 1997), which involves walking 20 meters, turning, stepping, and stair ascent and descent components. The maximum possible score on the DGI is 24 and scores of 19 or less have been related to increased incidence of falls in the elderly (Shumway-Cook et al., 1997). The Activities-Specific Balance Confidence Scale "ABC Scale" (Powell & Myers, 1995) assessed self-reported balance confidence during different activities. Specifically, participants were asked to report their level of confidence from 0% (i.e., no confidence) to 100% (i.e., complete confidence) in performing activities such as walking in a crowded area or walking up and down stairs. A summary score was derived by averaging responses across the sixteen items.

Procedure

All participants were tested individually at the PERFORM Centre of Concordia University. During an initial screening session, they were administered assessments of cognition, mobility and audition. Participants from Study 1 (*n* = 144) were also administered the DGI during this initial session. Eligible participants then participated in subsequent experimental and intervention sessions, which are described elsewhere (see Bruce et al., 2017; Bruce et al., 2018; Lai et al., 2017).

Results

Data Screening. All measures were checked for outliers (i.e., > 3.5 SD) both in terms of intra-individual and interindividual variability and extreme scores were winsorized.

Background measures. Descriptive statistics and between-groups analyses are shown for all background measures in Table 1. A series of independent samples *t*-tests were first performed to test whether the groups were comparable on the aforementioned dependent measures between the two studies. Correlations among the measures are presented in Table 2.

Confirmatory Factor Analysis. Confirmatory factor analysis was performed using MPLUS (Version 8.0) as we were interested in fitting the data to a model that is supported by empirical research. Before testing the latent constructs, the LSEQ was reverse coded (e.g., 70% becomes 30%) since greater values on this measure conventionally indicate better hearing, while a higher PTA is indicative of worse hearing. Several indices were then used to assess goodness of fit of the model, including the comparative fit index (CFI), Tucker–Lewis index (TLI), root mean square error of approximation (RMSEA) and standardized root mean square residual (SRMR). According to Kelloway (2015), CFI and TLI values greater than 0.95 and RMSEA and SRMR values lower than 0.08 indicate good fit between the hypothesized model and the observed data. The model tested was a two-factor model that assumes that Cognition is comprised of the MoCA, Digit Symbol and Letter-Number Sequencing and that Hearing is comprised of the Listening Self Efficacy Questionnaire and PTA (see Figure 1). The results indicated that the model exhibited good overall fit indices: CFI = 1.00, TLI = 1.01, SRMR = .02, RMSEA = .00, 90% CI [.00, .10]. A three-factor model including a Mobility construct comprised of the DGI and ABC exhibited poor fit and therefore was not used for subsequent analyses.

Hypothesized Model. As show in Figure 1, our hypothesized model depicts relationships among the variables of hearing, cognition and mobility for the sample of combined OAH and ARHL. This model had good overall fit indices: CFI = .95, TLI = .89, SRMR=.05, RMSEA=.08, 90% CI [.03, .13]. As shown in Figure 2, hearing was negatively associated with cognition, β = -0.44, p = .003 and with balance confidence, β = -0.63, $p < .001$. To investigate the impact of chronological age on hearing in the main hypothesized model (Figure 1), chronological age was added to the model with good overall fit indices: CFI = .93, TLI = .84, SRMR=.04, RMSEA=.09, 90% CI [.05, .13] (see Figure 3). Importantly, the association between hearing and balance confidence was maintained, β = -0.91, $p < .001$.

Subjective and Objective Models. The hearing and mobility measures were then subdivided by self-efficacy and objective measures to separately investigate their association with cognition. Specifically, the objective model included indices of hearing acuity and global mobility (PTA and DGI, respectively); and the self-efficacy model included indices of hearing self-efficacy and balance confidence (LSEQ and ABC, respectively). The model for objective measures had good overall fit indices: CFI = 1.00, TLI = 1.07, SRMR=.01, RMSEA=.00, 90% CI [.00, .00] (see Figure 4). Namely, objective hearing (PTA) was negatively associated with cognition, β = -0.37, $p < .001$ and cognition was positively associated with objective mobility (DGI), β = 0.45, $p < .001$.

Based on these findings, a mediation analysis was run on the objective measures to investigate whether the relation between objective hearing and mobility is mediated through cognition. This model had good overall fit indices: CFI = 1.00, TLI = 1.07, SRMR=.01, RMSEA=.00, 90% CI [.00, .00] (see Figure 5). Consistent with the previous model (Figure 4), objective hearing (PTA) was negatively associated with cognition, $\beta = -0.39$, $p < .001$, cognition was positively associated with objective mobility (DGI), $\beta = 0.55$, $p < .001$, and the relation between objective hearing (PTA) and objective mobility (DGI) was not significant, $\beta = -0.15$, $p = .134$. In addition, the relation between objective hearing (PTA) and objective mobility (DGI) was mediated through cognition, $\beta = -0.22$, $p < .001$.

The model for self-efficacy measures also had good overall fit indices: CFI = .99, TLI = .97, SRMR=.03, RMSEA=.04, 90% CI [.00, .12] (see Figure 6). Specifically, all hypothesized associations were significant such that hearing self-efficacy (LSEQ) was negatively associated with cognition, $\beta = -0.26$, $p = .021$ and with balance confidence (ABC), $\beta = -0.46$, $p < .001$. Moreover, cognition was positively associated with balance confidence (ABC), $\beta = 0.31$, $p < .001$.

Discussion

The purpose of the current study was to investigate the associations between cognition, hearing and motor functioning in a sample of older adults. Given the importance of both objective functioning and self-efficacy in this population in influencing outcomes such as social engagement and falls, our models were subdivided according to objective and self-efficacy measures as a secondary analysis. We predicted that hearing loss would be negatively associated with mobility and that this association would be influenced by cognitive status. Secondly, we predicted that self-efficacy would be an important contributor to understanding the association between these measures in aging, given that persons with sensory impairment generally report less mastery of their environment and daily activities which likely include demands on hearing and mobility.

Using our hypothesized model, we first confirmed previous work (e.g., Bush et al., 2015; Lin et al., 2011) in showing that hearing loss is associated with poorer cognitive functioning on both verbal and nonverbal cognitive measures. Given the possibility that chronological age might be contributing to the relation between hearing loss and decreased cognitive performance, we then added age to the model. However, given that age and peripheral hearing loss are also strongly correlated ($r = .497$), this statistical correction likely removed some of the variance associated with peripheral hearing loss in addition to any error variance (Martin, Ellsworth, & Cranford, 1991). Nevertheless, when chronological age was added to the model, increased hearing loss was associated with lower balance confidence consistent with previous work suggesting that older adults with hearing loss show decreased balance confidence (e.g., Bruce et al., 2017). These findings could suggest one mechanism by which older adults with hearing loss are at a higher risk of falls as fear of falling is associated with reduced physical and functional activities (Dionyssiotis, 2012) and decreased willingness to engage in such activities (Viljanen et al., 2009).

Considering the objective and self-efficacy measures in separate models generated different patterns of results. Using objective measures, we found that poorer cognitive performance was associated with decreased global mobility, replicating previous work that has shown relationships between working memory and processing speed with dual-task gait speed and gait variability (e.g., Holtzer et al., 2006; Yogev-Seligman et al., 2008). Although in the present findings, there was no direct association between objective hearing loss and mobility, a mediation analysis revealed that the association between greater hearing loss and lower mobility was mediated through lowered cognitive status. These findings are consistent with neuroimaging results wherein older adults demonstrate increased activation of frontal regions and decreased activation in the auditory cortex when performing a word perception in noise task (Wong et al., 2009). Similarly, within the domain of motor functioning, previous research has shown increased cerebral oxygenation in the prefrontal cortex among older adults during walking (Holtzer et al., 2011; Holtzer et al., 2015). Moreover, increased cerebral activation was positively associated with increasing dual-task attentional demands (Holtzer et al., 2011; Holtzer et al., 2015). Taken together, our findings are in line with the cognitive compensation viewpoint, which posits that age-related decline in motor and sensory abilities are compensated for through cognitive resources (Li & Lindenberger, 2002). The current findings add to previous experimental work demonstrating the involvement of cognitive resources in hearing and balance among older adults with age-related hearing loss (Bruce et al., 2017; Lau et al., 2016; Nieborowska et al, in press).

A novel addition to this growing area of research is the consideration of self-efficacy in the auditory and motor domains. Our secondary analyses of listening self-efficacy, balance confidence, and cognitive performance revealed significant associations between all variables in the model, including a direct association between listening self-efficacy and balance confidence not found in the objective model. Previous work has suggested that older adults with hearing impairment report more effortful listening and that listening effort depends not only on hearing difficulties, but also on the listener's motivation to expend mental effort in the challenging situations of everyday life (Pichora-Fuller, 2016; Pichora-Fuller et al., 2016). The current results further suggest that self-efficacy in the domain of hearing is an important predictor of balance confidence. These results are consistent with work done in the domain of life-space mobility which has demonstrated that perceived decline in hearing is associated with decreased mobility and engagement with society (Polku et al., 2015), and that perceived benefit from hearing aid use was associated with better life-space mobility scores (Polku et al., 2016).

These self-efficacy findings also extend work done by Heyl and Wahl (2012) who found stronger associations between cognitive functioning and individuals' feelings of subjective autonomy and environmental mastery among sensory impaired older adults, which also functioned to undermine their confidence in mastering day-to-day life. The current findings suggest one possible explanation for Heyl's results, wherein self-efficacy in hearing and motor domains may have influenced older adults' confidence in behaviour-related everyday functioning.

Limitations and Future Directions: A limitation of the current study is that we did not include a measure of cognitive self-efficacy. Future studies could include such a measure to investigate whether older adults' perceptions of their cognitive abilities are an important contributor to understanding self-efficacy in other domains (Hertzog & Dunlosky, 2011; Lachman, 2006). Future work should also add measures of motor and sensory functioning to generate more stable latent constructs, as well as a measure of central hearing loss in addition to the current assessment of peripheral hearing. Moreover, our sample consisted of healthy older adults with mostly mild hearing loss. Future studies could include individuals with more severe hearing loss (e.g., hearing aid users) and/or physical frailty (e.g., fallers) to determine whether the observed relationships hold, or are strengthened in less healthy samples (Heyl & Wahl, 2012). Lastly, future studies could use a longitudinal design to investigate the predictive value of these associations over time.

Conclusions and Implications: Together, the current results suggest that both objective assessments and self-efficacy measures are important contributors to understanding the relations among cognition, hearing, and mobility. Moreover, the findings underscore the role of cognitive compensation in mediating the relationship between hearing and mobility. As such, they suggest that cognitive remediation through computerized training or aerobic exercise (Bherer et al., 2013; Bruce et al., 2017; Lustig et al., 2008) may play an important role in improving mobility and functional capacity for older adults with hearing loss.

Table 1

Means and standard deviations for all baseline measures

Source	*Study One (n = 144)*	*Study Two (n = 76)*	*Pooled Sample (n = 218)*	*p value*
Age (years)	69.03 (6.00)	69.29 (5.70)	69.11 (5.89)	.766
Education (years)	16.32 (3.39)	16.34 (3.30)	16.33 (3.35)	.964
Average Hearing Threshold (dB)	25.65 (8.63)	24.34 (8.63)	22.49 (8.05)	.288
LNS (max 30)	18.91 (2.82)	18.57 (2.54)	18.79 (2.72)	.380
DS (max 135)	63.94 (13.48)	63.78 (14.44)	63.88 (13.79)	.933
MoCA (max 30)	26.65 (2.48)	26.68 (2.68)	26.66 (2.54)	.931
ABC (max 100)	93.34 (7.25)	94.47 (6.48)	93.67 (7.02)	.305
LSEQ (max 100)	81.78 (13.10)	83.48 (13.11)	82.29 (13.09)	.408
DGI (max 24)	22.75 (1.62)		---	

Note. p value refers to the independent samples t tests comparing the two study groups. Average Hearing Threshold = average of the minimum tone detection thresholds assessed across 500, 1000, 2000 and 3000 Hz from the better ear. LNS = Letter-Number Sequencing. DS = Digit Symbol. MoCA = Montreal Cognitive Assessment. ABC = Activities-Specific Balance Confidence Scale. LSEQ = Listening Self-Efficacy Questionnaire. DGI = Dynamic Gait Index.

Table 2

Intercorrelations Among the Measured Variables for the Combined Sample

Variable	1.	2.	3.	4.	5.	6.	7.	8.
1. Age	1							
2. PTA	.497**	1						
3. LSEQ	.382**	.360**	1					
4. ABC	-.331**	-.287**	-.535**	1				
5. DGI	-.364**	-.321**	-.245**	.340**	1			
6. MoCA	-.142*	-.187**	-.080	.134	.244**	1		
7. LNS	-.266**	-.184**	-.223**	.220**	.275**	.297**	1	
8. DS	-.362**	-.286**	-.171*	.326**	.375**	.413**	.411**	1

Note. * indicates correlations which are significant at the $p < 0.05$ level and ** indicates correlations which are significant at the $p < 0.01$ level. PTA = average pure tone threshold (500, 1000, 2000 and 3000 Hz). LSEQ = Listening Self Efficacy Questionnaire reverse scored. ABC = Activities-Specific Balance Confidence Scale. DGI = Dynamic Gait Index. MoCA = Montreal Cognitive Assessment. LNS = Letter-Number Sequencing. DS = Digit Symbol.

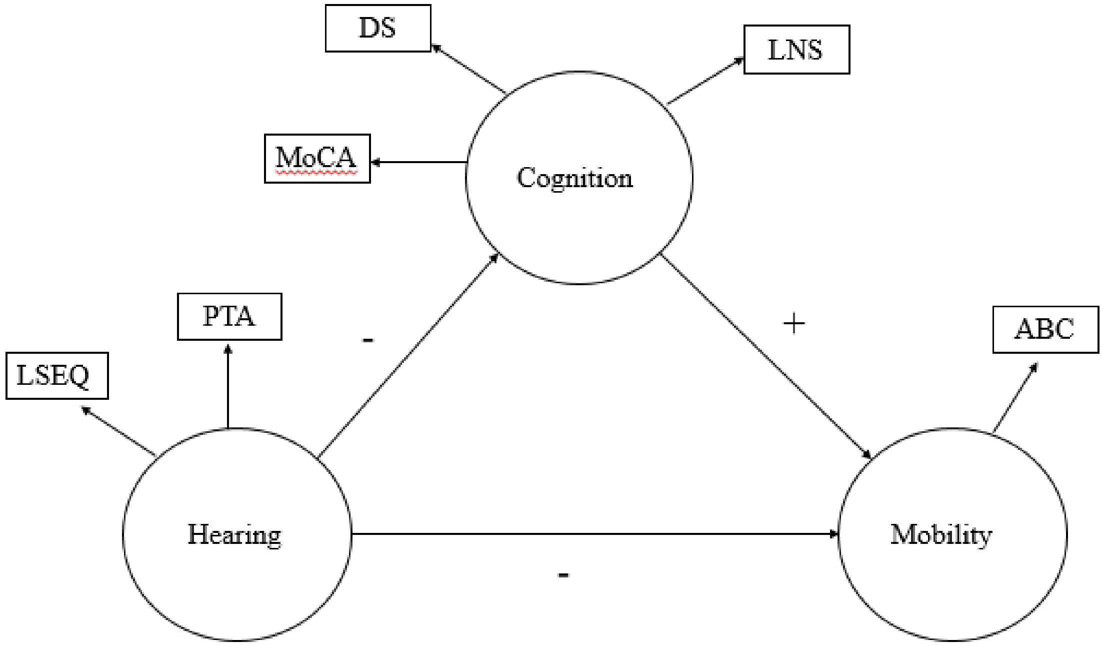

Figure 1. Hypothesized model. *Note.* LSEQ = Listening Self Efficacy Questionnaire reverse scored. PTA = average pure tone threshold (500, 1000, 2000 and 3000 Hz). MoCA = Montreal Cognitive Assessment. DS = Digit Symbol. LNS = Letter-Number Sequencing. ABC = Activities-Specific Balance Confidence Scale.

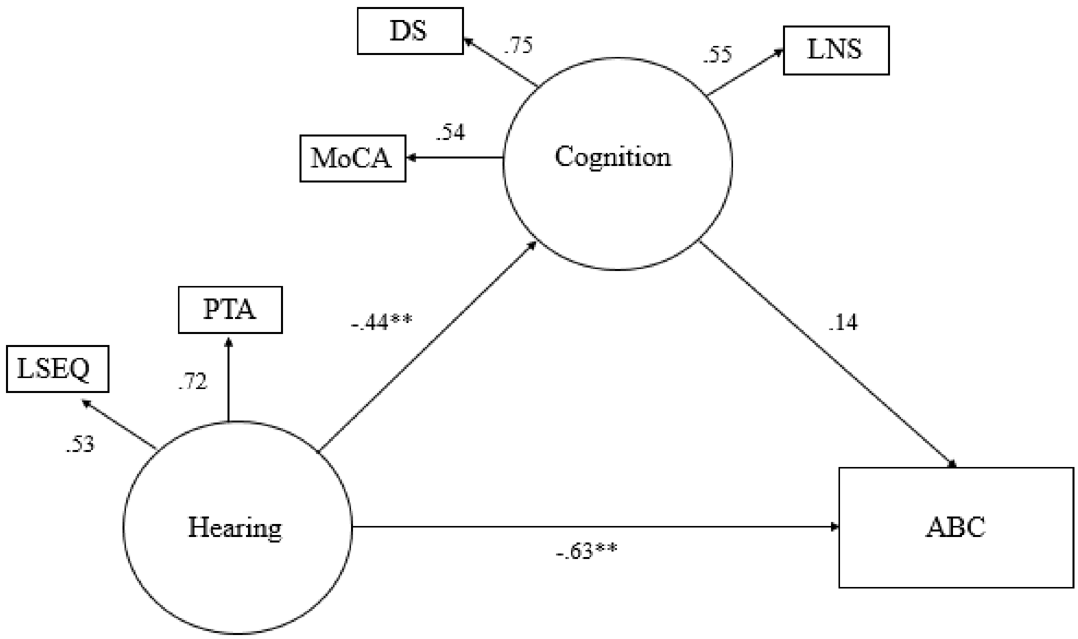

Figure 2. SEM for the hypothesized model. *Note.* Path coefficients are standardized regression weights. ** indicates path coefficients which are significant at the $p < .05$ level. LSEQ = Listening Self Efficacy Questionnaire reverse scored. PTA = average pure tone threshold (500, 1000, 2000 and 3000 Hz). MoCA = Montreal Cognitive Assessment. DS = Digit Symbol. LNS = Letter-Number Sequencing. ABC = Activities-Specific Balance Confidence Scale.

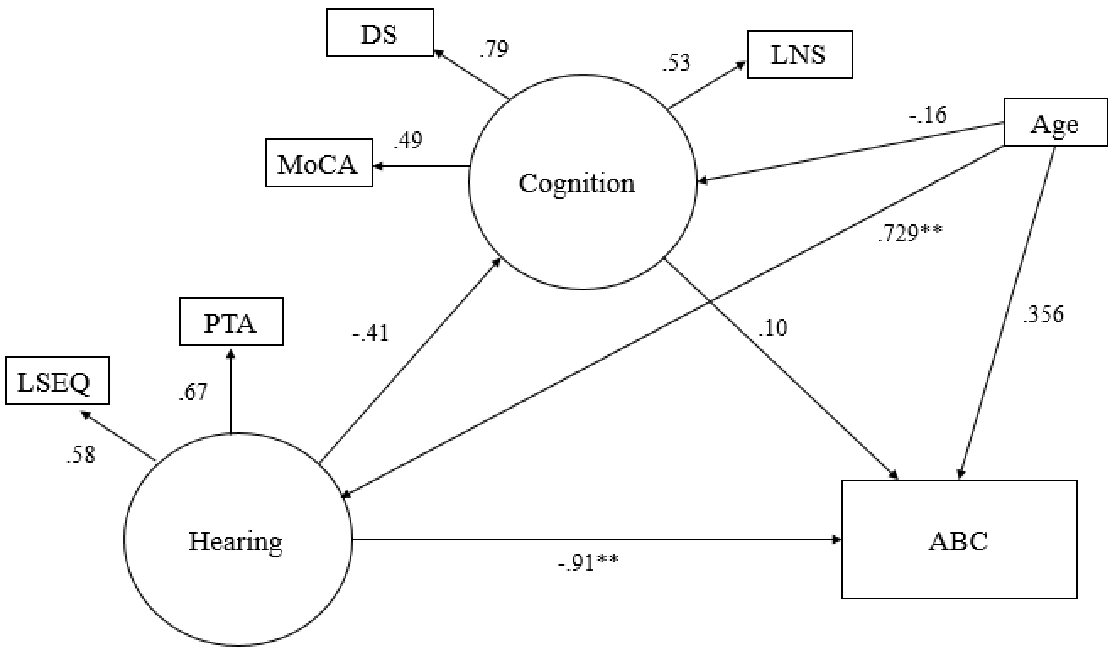

Figure 3. SEM for the hypothesized model including age in the model. *Note.* Path coefficients are standardized regression weights. ** indicates path coefficients which are significant at the p < .05 level. Age = Chronological Age. LSEQ = Listening Self Efficacy Questionnaire reverse scored. PTA = average pure tone threshold (500, 1000, 2000 and 3000 Hz). MoCA = Montreal Cognitive Assessment. DS = Digit Symbol. LNS = Letter-Number Sequencing. ABC = Activities-Specific Balance Confidence Scale.

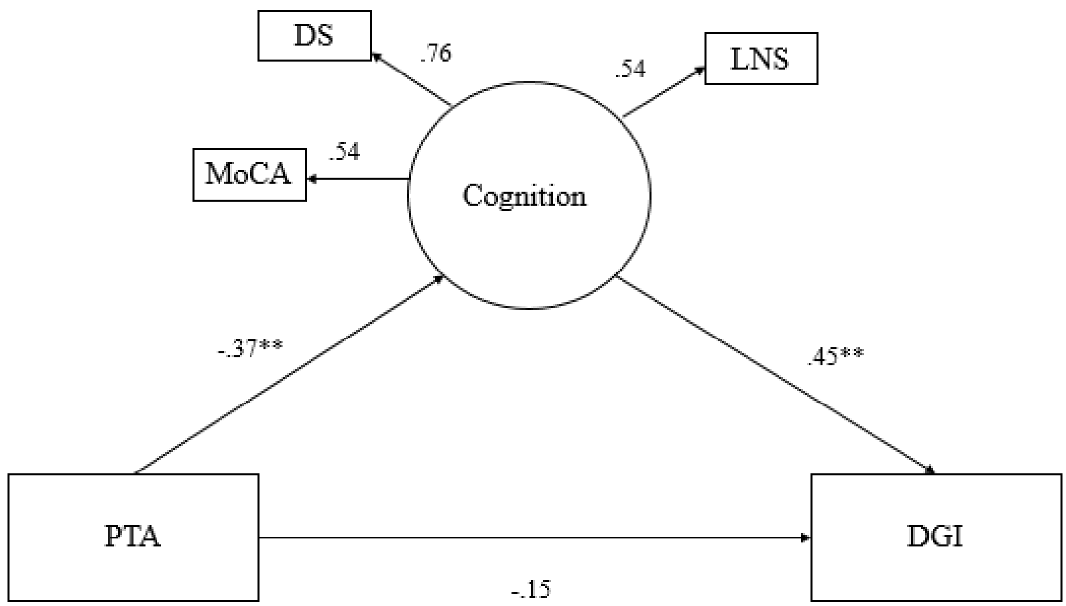

Figure 4. SEM for the hypothesized model using objective measures. *Note. n* = 132. Path coefficients are standardized regression weights. ** indicates path coefficients which are significant at the p < .05 level. PTA = average pure tone threshold (500, 1000, 2000 and 3000 Hz). MoCA = Montreal Cognitive Assessment. DS = Digit Symbol. LNS = Letter-Number Sequencing. DGI = Dynamic Gait Index.

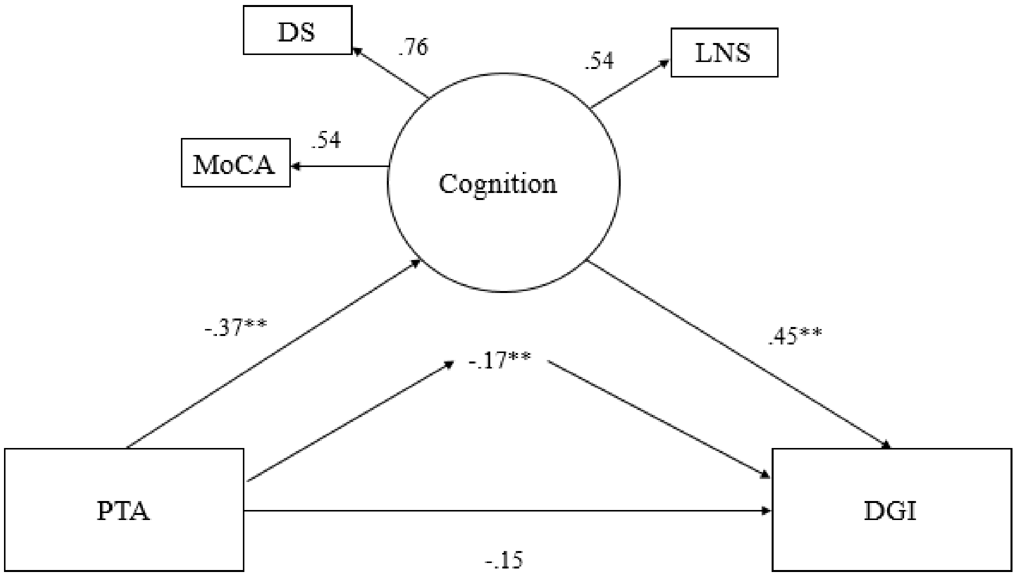

Figure 5. SEM for the hypothesized model using objective measures and testing mediation of cognition on relation between hearing and mobility. *Note.* n = 132. Path coefficients are standardized regression weights. ** indicates path coefficients which are significant at the $p < .05$ level. PTA = average pure tone threshold (500, 1000, 2000 and 3000 Hz). MoCA = Montreal Cognitive Assessment. DS = Digit Symbol. LNS = Letter-Number Sequencing. DGI = Dynamic Gait Index.

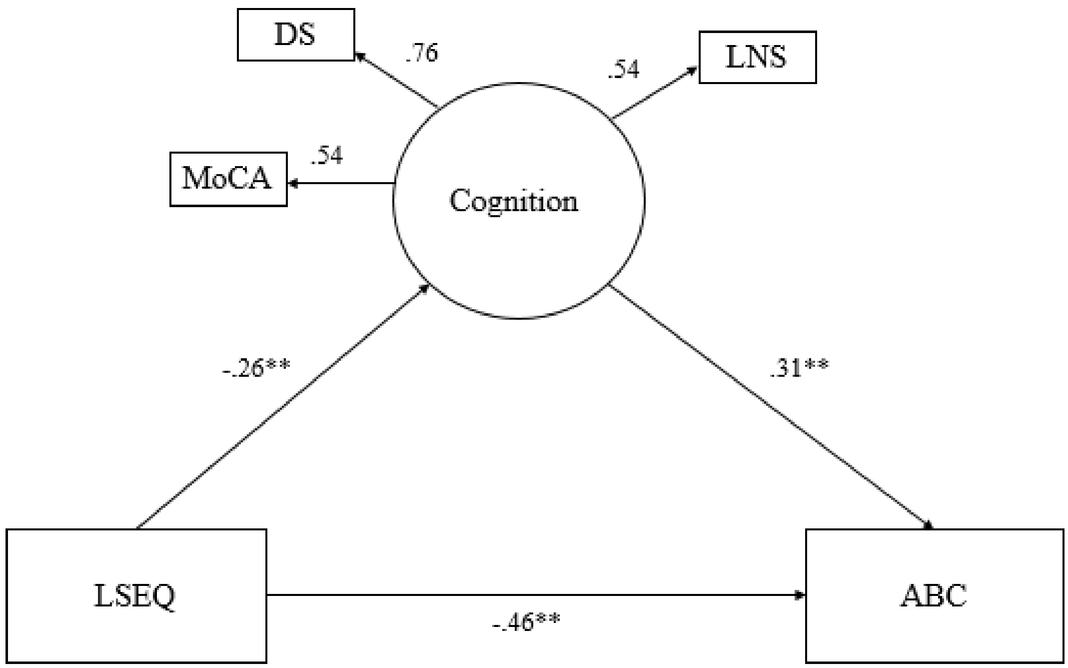

Figure 6. SEM for the hypothesized model using self-efficacy measures. *Note.* Path coefficients are standardized regression weights. ** indicates path coefficients which are significant at the p < .05 level. LSEQ = Listening Self Efficacy Questionnaire reverse scored. MoCA = Montreal Cognitive Assessment. DS = Digit Symbol. LNS = Letter-Number Sequencing. ABC = Activities-Specific Balance Confidence Scale.

CHAPTER 5

GENERAL DISCUSSION

As previously reviewed, a growing body of research suggests that both hearing and mobility increasingly rely on cognitive resources with age. Given the central role of cognition in both sensory and sensorimotor aging, the current studies aimed to investigate the role of cognition in both hearing and mobility domains among older adults using experimental, intervention and modeling approaches. In Paper 1 (Bruce et al., 2017) we investigated the impact of increasing cognitive load among older adults with and without hearing loss. Specifically, we challenged them with a cognitive-motor dual-task while also including an element of auditory challenge using noise. As hypothesized, compared to their normal hearing counterparts, older adults with hearing loss demonstrated greater dual-task costs particularly in challenging conditions. This cost was characterized by a drop in cognitive performance while posture remained similar to that observed under single-task conditions. Given the findings of Paper 1, we aimed to strengthen cognitive resources in Paper 2 (Bruce et al., 2018), along the lines of the scaffolding enhancement component of Reuter-Lorenz's STAC model (Park & Reuter-Lorenz, 2009). Using this approach, we demonstrated that strengthening cognition through sequentially combined cognitive-physical training benefitted dual-task outcomes measures. This effect was particularly evident during the more challenging auditory conditions, and among those with hearing loss. Beyond considering these group-wise effects, in Paper 3 (Bruce et al., in preparation) we investigated individual differences in hearing, cognition, and self-efficacy, which might influence mobility functioning. Results from structural equation modeling revealed that greater hearing loss was associated with decreased cognition and mobility and lower listening self-efficacy was associated with decreased balance confidence.

Linking Hearing Loss and Mobility Through Cognition

Reduction of Cognitive Capacity

The current work is consistent with previous studies demonstrating that both listening and mobility increasingly rely on cognitive resources with age (e.g., Brown et al., 1999; Gosselin & Gagn*é*, 2011; Tun et al., 2009). The current work is novel in combining these two domains and challenging older adults with and without age-related hearing loss using a cognitive-motor dual-task paradigm. Using this approach, we showed a dual-task cost in the cognitive domain among older adults with age-related hearing loss. Specifically, despite equating the SNR for our participants, older adults with age-related hearing loss demonstrated a dual-task performance decrement on the auditory cognitive task, while maintaining their postural response during challenging dual-task conditions. Importantly, this performance cost was not observed among normal hearing older adults who exhibited a similar postural strategy. Consistent with the idea of cognitive compensation (Li & Lindenberger, 2003), this pattern of results suggests that hearing loss is associated with increased competition for cognitive resources particularly in challenging dual-task conditions.

Expansion of Cognitive Capacity

Given the observation that older adults with age-related hearing loss exhibited greater dual-task costs than normal hearing older adults, one possible implication is to increase cognitive capacity to reduce these costs. Other researchers have aimed to improve single and dual-tasking among older adults using single domain or combined training to strengthen cognitive capacity. Among healthy older adults, single domain cognitive training has been shown to benefit executive functions (Lustig et al. 2009) and transfer to motor tasks including measures of postural control (Li et al., 2010) and gait (Smith-Ray et al., 2013; Verghese et al., 2010). However, the literature is mixed regarding the increased efficacy of single versus combined training on motor (Agmon et al., 2014; Fraser et al., 2017) and cognitive (Zhu et al., 2016) outcomes. Moreover, there is a high degree of heterogeneity in the types of training tasks used and how researchers combine cognitive and physical training. Specifically, tasks can be trained separately (i.e., sequentially) or at the same time (i.e., simultaneously). Additionally, combined training formats are often compared to single domain cognitive or physical training or to a placebo to assess the potential synergistic effects of combined training (Agmon et al., 2014; Fraser et al., 2017; Zhu et al., 2016). Importantly, aside from the present work, no study has directly compared simultaneous and sequential approaches while specifically targeting a hearing loss population. While simultaneous training may be more beneficial as it mimics real-life conditions, reduces training time and costs (Theill et al., 2013) and trains coordination between cognitive and motor tasks (Zhu et al., 2016), there might also be a cost associated with dividing attention between the trained cognitive task and the concurrent motor task (Li et al., 2001). Our second study therefore compared simultaneous and sequential cognitive-physical combined training formats on cognitive-motor dual-task outcomes, while also sampling older adults with hearing loss.

With respect to the intervention design in Paper 2, we opted to omit a control group given that the efficacy of each training component had already been established (e.g., Desjardins-Crépeau, 2016; Fraser et al., 2017). Moreover, in a recent study using the same training components with a similar sample of healthy older adults, an active control condition (stretching plus computer lessons) did not yield pre-post changes or learning effects (Fraser et al., 2017). Another consideration is the total amount of time spent in training. While the sequential training group received 30 minutes of cognitive training followed by 30 minutes of physical training (1-hour total), the simultaneous group received 30 minutes of concurrent cognitive and physical training (30 minutes total). Although the total training time differed between the two groups, training was designed such that both groups received the same "dosage".

In Paper 2, it was found that sequential training was more effective in improving auditory working memory performance particularly in challenging low volume auditory conditions, which have previously been shown to be detrimental to older adults' working memory performance (Baldwin & Ash, 2011). After subdividing the sample by hearing status, we showed that older adults with age-related hearing loss appeared to benefit from training regardless of format in these same challenging auditory conditions. In contrast, while all participants demonstrated gains on a measure of global mobility, there was no transfer or format effect on postural outcome measures.

The differential benefits of sequential training on the cognitive and motor outcome measures can be understood by considering the literature on cognitive aging and transfer effects. That is, the magnitude of transfer to untrained measures depends on its relationship to the trained task (Dahlin et al., 2008) in that training is likely to benefit tasks that share surface features or strategies with the trained task (Hertzog et al., 2008). Consistent with this idea, in the current work, transfer of training was most prominent for the near transfer task of auditory working memory. This near transfer was also supported through significantly greater gains for the sequential group on an independent measure of working memory as compared to the simultaneous group (Lai et al., 2017). Presumably the sequential format of training was more effective than the simultaneous format because it allowed participants to practice their dual-task processing without the distraction of simultaneous cycling. This is consistent with what was observed in the training phase data in that there was a slightly higher rate of progress on DT performance in the sequential group when compared to the simultaneous group but comparable progress on the aerobic training task.

In contrast, there was less far transfer to mobility outcome measures, which likely share less functional overlap with the trained tasks. However, this finding contrasts with previous work (Li et al., 2010), which demonstrated transfer to postural outcomes using a similar cognitive training task. Although the current study used similar outcomes measures of dual-task single support, the previous work demonstrated training-related gains particularly when participants were asked to perform this condition with eyes closed. Given that older adults are more susceptible to reduced proprioceptive input (Redfern et al., 1997; Teasdale et al.,1993), it is possible that this manipulation resulted in greater recruitment of cognitive resources thus rendering it more sensitive to cognitive training. When considering the mobility outcomes, another possibility is that training reduced the amount of cognitive resources needed to perform the motor task, thus freeing up resources for the secondary auditory cognitive task (Godde & Voelcker-Rehage, 2017).

Overall, the findings in Paper 2 demonstrate that strengthening cognitive resources through sequentially combined training can be beneficial to challenging dual-task cognitive-motor outcomes particularly for older adults with age-related hearing loss. This finding is consistent with other intervention work with a hearing-impaired population which shows that intervention with amplification devices (e.g., hearing aid, cochlear implants) can benefit gait and balance (Shayman et al., 2017) and that working memory and auditory training can improve scores on measures of competing speech and complex cognitive tasks which assess executive function (Ferguson & Henshaw, 2015).

Cognitive Mediation

Another approach is to go beyond the group-wise effects that were investigated in the first two papers and consider individual differences in hearing acuity and cognitive status which might play a role in predicting mobility. Using multivariate approaches, it has previously been demonstrated that older adults with hearing loss show lower scores on both verbal and nonverbal cognitive measures (e.g., Lin et al., 2011) as well as poorer physical functioning (e.g., Chen et al., 2015). Moreover, others (Heyl & Wahl, 2012) demonstrated that older adults with sensory impairment rely more heavily on cognitive resources to perform everyday activities and show decreased confidence in mastery of their environment. However, to date, cognitive motor and hearing domains have not often been considered together, nor have self-efficacy and objective assessments of hearing and mobility been commonly compared.

In Paper 3, replicating previous work (e.g., Lin et al., 2011), hearing loss was associated with decreased cognition and reduced balance confidence. Additionally, the association between lower objective hearing loss and greater mobility was mediated through higher cognitive status, which is consistent with neuroimaging work demonstrating increased brain activation during hearing (e.g., Wong et al., 2009) and mobility (e.g., Holtzer et al., 2011; Holtzer et al., 2015) tasks among older adults. Moreover, this finding is in line with cognitive compensation (Li & Lindenberger, 2002), wherein older adults compensate for declines in motor and hearing domains by recruiting cognitive resources.

In addition, self-efficacy (Bandura, 1977) appeared to be an important contributor to understanding the relation between hearing and mobility in that lower listening self-efficacy was directly associated with decreased balance confidence. This work is consistent with other studies which demonstrate that older adults with hearing loss expend more listening effort (Pichora-Fuller, 2016; Pichora-Fuller et al., 2016) and that perceived hearing loss is associated with decreased mobility and engagement (Polku et al., 2015). Our study also extends work by Heyl and Wahl (2012), who found that older adults with sensory impairment demonstrated decreased subjective autonomy and environmental mastery, particularly with respect to "daily activities of living". The current work adds to this literature by explicitly measuring listening self-efficacy and balance confidence, which may contribute to this population's reduced confidence in behaviour-related everyday activities. Ultimately, this decreased self-efficacy in both domains may lead to a process of disengagement and deconditioning. Future studies could include an assessment of activities of daily living to investigate whether mobility self-efficacy is predictive of daily activities.

Postural Prioritization

A common theme that relates to much of the present empirical work is postural prioritization, the observation of increased costs in the cognitive domain during cognitive-motor dual-tasking (Brown et al., 1999; Li et al., 2005; Little & Woollacott, 2014; Redfern et al., 2002; Verghese et al., 2007). Consistent with previous work, our experimental and intervention studies (Papers 1 and 2) demonstrated that older adults tended to prioritize posture relative to listening performance. Specifically, our dual-task experimental work showed that older adults with hearing loss exhibited a drop in performance from single- to dual-task conditions on the secondary cognitive task in order to maintain posture on the mobility task. Turning to the intervention work and specifically to the training phase cognitive data, there was a trend such that older adults who were trained simultaneously had lower gains on the cognitive training task but similar performance on the aerobic training task, compared to those who were trained sequentially. That is, measured both objectively and subjectively, the simultaneous group showed lower gains on the cognitive training task across sessions. These findings suggest that older adults prioritized the aerobic training task at the expense of cognitive training indicating a cost to dividing attention. Together, these results suggest that older adults with and without hearing loss appear to prioritize posture in cognitive-motor dual-task conditions.

Theoretical Implications

Overall, the current work has demonstrated that cognition is involved in both hearing and mobility among an older adult population, particularly among those with age-related hearing loss. These findings are largely consistent with the theory of cognitive compensation (Li & Lindenberger, 2002) which proposes that declining peripheral functioning is compensated for through the recruitment of cognitive resources. Within this framework, increased demands on hearing, motor, or cognitive abilities would result in greater competition for common cognitive resources. This effect is evident in the current work wherein cognitive involvement was more pronounced in challenging conditions (e.g., dual-tasking, performing an auditory working memory task in noise) and among those with reduced peripheral hearing. The current work is also consistent with the idea of compensatory scaffolding (Park & Reuter-Lorenz, 2009), in that strengthening cognitive resources using combined training improved performance on cognitive-motor dual-task outcome measures with an auditory working memory component.

Other theories of compensation (Cabeza, 2002; Park & Reuter-Lorenz, 2009) suggest that older adults demonstrate compensatory frontal and bilateral brain activation to maintain behavioural performance. Although the current work did not include functional neuroimaging measures, previous work has demonstrated a link between brain volume in frontal regions (e.g., dorsolateral prefrontal cortex) and mobility parameters such as gait speed (Rosano et al., 2007). Others have demonstrated patterns of neural compensation during real-time walking performance, in that greater activation in prefrontal regions is observed with increasing cognitive demands during walking (Holtzer et al. 2011; 2015). Given this previous work, it is possible that older adults and particularly those with hearing loss would have demonstrated increased frontal or bilateral brain activation in response to challenging conditions (e.g., dual-tasking, performing an auditory working memory task in noise) as a means of maintaining their mobility performance. Future training studies could incorporate functional imaging techniques into pre- and post-training assessments of dual-task posture and gait to investigate the impact of training on compensatory brain activation.

Limitations and Future Directions

One limitation of our studies is that we tested older adults with mild hearing loss who were free from mobility impairments. Particularly in Study 2, the older adults were very fit relative to the general aging population, given the strict inclusion criteria concerning readiness to exercise. Future studies could sample older adults with more profound hearing loss or mobility difficulties who would likely exhibit greater competition for cognitive resources particularly in challenging dual-task conditions. These clinical populations would be particularly important to investigate given their risk for cognitive decline, incident dementia (Lin et al., 2013; Lin et al., 2011) and falls (Viljanen et al., 2009).

A second limitation of our studies is the use of cross-sectional data, particularly with respect to modeling. Future studies could take a longitudinal approach perhaps even starting in midlife to better elucidate the mechanisms accounting for the relation between hearing loss, decreased mobility and reduced cognition (Pichora-Fuller & Schow, 2017). These studies would also have implications for interventions which could be implemented earlier on to prevent decline in old age. Other approaches which are currently underway include implementing interventions such as physical exercise or hearing aid intervention (e.g., Deal et al., 2017) to examine physical, cognitive and hearing outcome measures longitudinally.

Another limitation of our studies is that we did not include an objective measure of vestibular dysfunction to complement the objective assessment of mobility and self-reported falls and vertigo. This consideration is important given the role of vestibular dysfunction in falls (Agrawal, Carey, Della Santina, Schubert, & Minor, 2009) and the possibility of concomitant cochlear and vestibular dysfunction in a hearing impaired population (Lin & Ferrucci, 2012). However, previous work has demonstrated that the association between hearing loss and falls remained even when controlling for objectively assessed vestibular dysfunction (Lin & Ferrucci, 2012). Regardless, future studies which include a hearing loss population could incorporate an objective clinical assessment of vestibular impairment (Jacobson & Shepard, 2008).

Lastly, a limitation of our studies is that our hearing loss samples were typically older and comprised of more men. However, these demographic characteristics are strongly correlated with hearing loss and therefore our samples were representative of this population (Stenklev & Laukli, 2004). Moreover, controlling for age with this population is challenging as age is strongly associated with peripheral hearing loss (Stenklev & Laukli, 2004) and therefore, controlling for age likely removes some of the variance associated with hearing loss in addition to error variance (Martin et al., 1991). Nevertheless, after controlling for age in two of our studies where samples differed in age, the majority of our findings remained statistically significant. This is consistent with previous epidemiological work which demonstrates correlations between hearing loss and decreased cognition (Lin, 2011; Lin et al., 2011) and falls (Viljanen et al., 2009) even after correcting for chronological age.

Clinical Implications

Having demonstrated using a variety of experimental and analytic techniques, the involvement of cognitive capacity in audition and motor performance, the present work suggests that targeted cognitive training could be used to complement more traditional audiological or physical rehabilitation. While traditional audiological rehabilitation entails auditory training, hearing aid use, patient education and counseling (Ferguson & Henshaw, 2015), physical rehabilitation often includes encompasses both active (e.g., exercise) and passive (e.g., therapeutic modalities) methods to maintain or improve mobility, physical activity, and overall health and wellness (Canadian Physiotherapy Association, 2012). Extending rehabilitation to include cognitive training may be particularly beneficial in challenging everyday situations which draw more heavily on cognitive resources such as cognitive-motor dual-tasking (e.g., walking and talking) or in the presence of noise (e.g., a busy restaurant). Since older adults and particularly those with hearing loss are at a greater risk for falls (Viljanen et al., 2009), this type of intervention may also serve to reduce the number of falls and help older adults maintain functional independence.

On a more practical level, the present results suggest that when working with older adults in clinics, it would be beneficial to reduce the amount of noise in the environment, use amplification devices when communicating, and reduce dual-tasking particularly when walking or providing important information. Due to the associations between cognition, hearing and mobility domains, clinicians (e.g., physiotherapists, audiologists, geriatricians) could embrace an interdisciplinary approach to treating older adults and consider referring patients to other services if they notice cognitive, mobility, or hearing difficulties. When completing cognitive screening, it would be important for clinicians to be aware of the impact of hearing loss on cognitive scores (e.g., MoCA; Dupuis et al., 2015) as well as the increased risk for cognitive decline and incident dementia (Lin et al., 2013; Lin et al., 2011) among this population. Moreover, given that older adults often have untreated hearing loss, clinicians could use screening questions to assess hearing loss and make a referral to an audiologist if warranted (Alzheimer's Society of Canada, 2017).

Since self-efficacy appears to be an important contributor to the relation between hearing loss and mobility, clinicians could consider approaches that would serve to increase confidence. Confidence is particularly important given the role it might play in older adults' willingness to engage in hearing and physical activities. Specifically, decreased self-efficacy may contribute to lower engagement in activities (Dionyssiotis, 2012; Polku et al., 2015; Viljanen et al., 2009), ultimately leading to a process of deconditioning and impairment. If not already implemented, suggestions to increase confidence may include tracking progress and continuous feedback on performance with respect to audiological and physical rehabilitation goals or tasks.

Conclusion

In sum, the current work was novel in using three different types of approaches to explicitly measure and investigate the role of cognitive resources in both mobility and hearing domains, while specifically sampling older adults with age-related hearing loss. Consistent with cognitive compensation (Li & Lindenberger, 2002), the current work demonstrated a role for cognition in mobility and hearing performance, with increasing competition in a hearing-impaired population. Moreover, self-efficacy emerged as another important contributor to the relation between hearing loss and mobility, suggesting that those with decreased listening self-efficacy also demonstrate reduced balance confidence. Together, these results suggest several mechanisms by which older adults with hearing loss are at a greater risk for falls (Viljanen et al., 2009) and have implications for future work and clinical practice.

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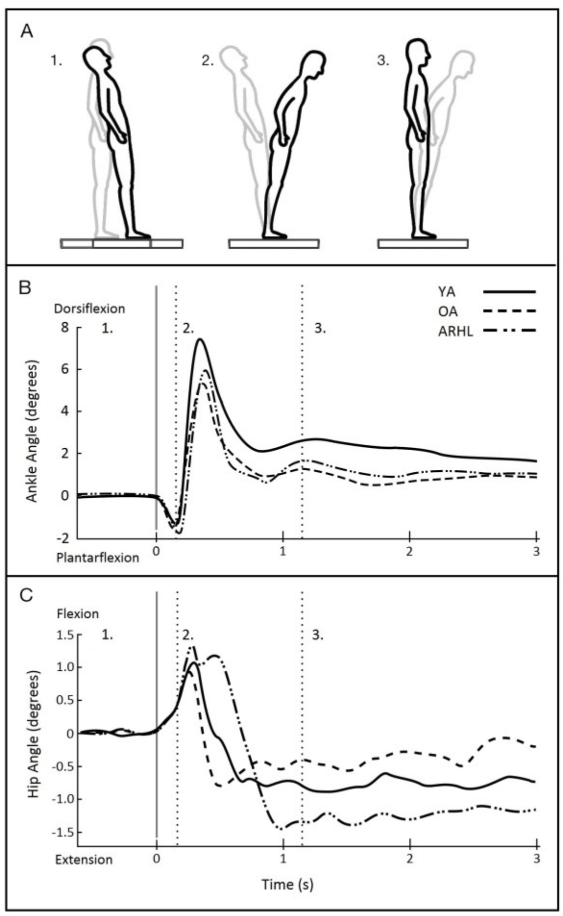
Appendix A

Panel A shows a representation of participants' postural response to the platform perturbation: 1. The perturbation phase, when the platform abruptly moves forward, 2. the reactive phase, when participants actively correct for the postural disturbance, 3. the recovery phase, when participants' posture slowly returns to its original position. Panel B is an individual trace for the ankle joint, with negative values indicating greater plantarflexion. Panel C is an individual trace for the hip joint, with negative values indicating greater hip extension. The vertical dotted lines in panels B and C denote the three postural phases. *Note.* YA = younger adults. OA = older adults. ARHL = older adults with age-related hearing loss.



Appendix B

Dual-Mixed Trial of the DT training task