Real-World Multitasking Challenges in Younger Adults and Older Adults with and without Subjective Cognitive Decline

by

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A thesis submitted in conformity with the requirements for the degree of Master of Arts
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Abstract

Age-related changes in postural control and/or cognition can be detrimental to multitasking performance. Previous studies investigating these effects have used paradigms not reflective of real-world challenges. Therefore, using a realistic multitasking paradigm in a virtual environment, this study examined age-related effects of performing a listening task while maintaining balance under varying levels of sensory/motor/cognitive challenge. Performance of individuals at potentially greater risk of cognitive decline (i.e., those with subjective cognitive decline (SCD)) was also evaluated. Results showed that older adults’ postural and listening performance was worse than younger adults, particularly under challenging conditions. Older adults with and without SCD exhibited comparable performance across conditions apart from the most challenging conditions, during which those with SCD demonstrated unexpectedly superior postural stability compared to those without. These findings demonstrate age-related decline in postural control and listening abilities, and suggest a prioritization of posture. Those with SCD did not demonstrate greater performance decrements.
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<tr>
<td>AD</td>
<td>Alzheimer’s Disease</td>
</tr>
<tr>
<td>ANOVA</td>
<td>Analysis of Variance</td>
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<tr>
<td>ANSI</td>
<td>American National Standards Institute</td>
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<tr>
<td>cm</td>
<td>Centimeters</td>
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<tr>
<td>COP</td>
<td>Center of Pressure</td>
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<tr>
<td>CRM</td>
<td>Coordinate Response Measure</td>
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<td>dB HL</td>
<td>Decibels Hearing Level</td>
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<tr>
<td>dB SPL</td>
<td>Decibels Sound Pressure Level</td>
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<tr>
<td>DDT</td>
<td>Dichotic Digits Test</td>
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<tr>
<td>DTT</td>
<td>Digit Triplet Test</td>
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<tr>
<td>EC</td>
<td>Eyes Open</td>
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<td>EO</td>
<td>Eyes Closed</td>
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<tr>
<td>ETDRS</td>
<td>Early Treatment Diabetic Retinopathy Study</td>
</tr>
<tr>
<td>Hz</td>
<td>Hertz</td>
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<tr>
<td>logMAR</td>
<td>Logarithm of the Minimum Angle of Resolution</td>
</tr>
<tr>
<td>M</td>
<td>Mean</td>
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<tr>
<td>MCI</td>
<td>Mild Cognitive Impairment</td>
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<td>MoCA</td>
<td>Montreal Cognitive Assessment</td>
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<td>OA</td>
<td>Older Adult</td>
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<tr>
<td>PTA</td>
<td>Pure-Tone Average</td>
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<tr>
<td>RAVLT</td>
<td>Rey Auditory Verbal Learning Test</td>
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<td>SCD</td>
<td>Subjective Cognitive Decline</td>
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<tr>
<td>SD</td>
<td>Standard Deviation</td>
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<td>SE</td>
<td>Standard Error</td>
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<td>TMT</td>
<td>Trail Making Test</td>
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<td>TUG</td>
<td>Timed Up and Go</td>
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<tr>
<td>VDC</td>
<td>Volts of Direct Current</td>
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<tr>
<td>WAIS</td>
<td>Wechsler Adult Intelligence Scale</td>
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<td>YA</td>
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1 Introduction

1.1 Overview

Successful performance of daily activities requires integration of sensory, cognitive, and motor inputs. However, when this coordination of multiple inputs is challenged, performing what one would often consider ‘easy’ everyday tasks may become more difficult. In mobility-related tasks, such as standing and walking, age-related changes to sensory, motor, and cognitive functions can affect one’s ability to successfully use and integrate necessary sensory-motor inputs, and appropriately allocate cognitive resources.

Postural control relies on perceptual processes to determine body position and orientation, and specific motor responses to maintain upright stance. It is well established that one’s ability to maintain postural stability changes with age. Specifically, age-related changes in sensory and motor processes are thought to contribute to older adults’ observed increases in postural sway (Maki & McIlroy, 1996; Maylor & Wing, 1996). There is also evidence to suggest that with age postural control becomes increasingly more cognitively demanding, with older adults exhibiting greater allocation of cognitive resources to postural tasks than younger adults (Boisgontier et al., 2013). This shift from automatic to controlled processing is thought to be a compensatory mechanism within the postural control system to offset declines in peripheral (e.g., receptor) and central (e.g., neural) levels of sensorimotor functioning (Boisgontier et al., 2013). As such, age-related declines in cognition and/or increases in cognitive load (e.g., the introduction of a cognitive task) can be detrimental to older adults’ ability to maintain postural stability. Dual-task paradigms, wherein a postural task is performed concurrently with a cognitive task, have been used in several studies to assess this association between postural control and cognition (e.g., Doumas, Smolders, & Krampe, 2008; Redfern, Jennings, Martin, & Furman, 2001; Shumway-Cook & Woollacott, 2000). For instance, in a study conducted by Shumway-Cook and Woollacott (2000), age-related differences in the attentional demands of postural control were examined by having younger and older adults perform a reaction time task during quiet stance (i.e., an upright posture in which the center of mass projects over the base of support). They found that the demands associated with maintaining an upright static standing posture were greater among older adults, particularly under more challenging sensory conditions (i.e., when the accuracy of visual and somatosensory inputs was reduced). As discussed in detail below,
increases in sensory, motor, and cognitive challenge within these dual-task paradigms can further expose differences in the availability and allocation of cognitive resources, and help identify circumstances under which an individual is at greater risk of losing their balance or falling.

However, previous dual-task findings have been obtained in predominantly artificial laboratory settings. While such testing environments allow for research questions to be addressed in a highly controlled and standardized manner, the impoverished laboratory contexts do not reflect the complexities of everyday, real-world settings. This, in turn, can make it difficult to assess the transferability of earlier findings to real-world experiences. Furthermore, the types of cognitive tasks that have been used in previous dual-tasking studies are not necessarily representative of the typical cognitive challenges faced in everyday environments and interactions. As discussed below, cognitive tasks commonly used in previous studies are rather abstract in nature as they target highly specific arithmetic, memory, or inhibitory abilities. Therefore, past paradigms have lacked ecological validity in that their testing environments and cognitive tasks have not accurately reflected realistic, real-world situations.

The importance of using ecologically valid paradigms in the assessment of cognitive-motor interactions and interference is beginning to receive more attention. With evidence to suggest that there is a difference in laboratory compared to real-world behaviours with respect to gait (Bock, & Beurskens, 2010) and cognitive performance (Verhaeghen, Marcoen, & Goossens, 1993), recent work has investigated the transferability of earlier findings in dual-task gait studies to more realistic settings (Janouch et al., 2018). However, to the best of my knowledge, the transferability of previous postural dual-task findings, specifically the effect of age on the performance of a postural task with a concurrent cognitive task, has not yet been assessed. Therefore, in this study, I introduced a paradigm that more accurately reflects realistic conditions under which one would typically perform an everyday task involving standing while listening. Using this paradigm, I looked to examine how younger and older adults’ postural and cognitive performance changed as a function of sensory, motor, and cognitive challenges.

Further, it would be expected that declines in cognition that extend beyond those deemed part of normal healthy aging would be associated with even greater detriments in dual-task performance, particularly under increasingly challenging sensory-motor-cognitive conditions. As such, performance of multitasking behaviours under challenging multisensory conditions may be
particularly sensitive to early stages of cognitive decline. There is some evidence suggesting that individuals with subjectively perceived declines in cognition but no measurable neuropsychological deficits using standard tests of cognitive functioning may be at greater risk of future clinically-significant declines (i.e., a later diagnosis of dementia) (Rabin, Smart, & Amariglio, 2017). Therefore, in this thesis, I also considered whether older adults with and without subjectively perceived declines in cognition exhibited worse postural and/or cognitive performance than same aged peers without subjective concerns about their cognition.

In the following sections, I will review literature describing the sensory, motor, and cognitive functions that underlie posture and summarize evidence of age-related differences in postural control. I will then briefly review how postural control is affected by increases in sensory, motor, and cognitive challenges, with particular focus on the simultaneous performance of a postural task with a cognitive task (i.e., dual-tasking). Subsequently, I will consider the nature and limitations of previously used cognitive tasks within the context of postural dual-task studies and introduce the idea of using an auditory processing dual-task approach. My focus will then shift toward describing how postural control and auditory processing are affected by atypical declines in cognition (i.e., mild cognitive impairment and dementia). Finally, I will describe the current conceptualization of subjective cognitive decline within the literature and consider the potential implications of examining postural-cognitive dual-task performance in this group in particular.

1.2 Postural control

When performing daily activities that involve standing or walking, we rely heavily on our ability to maintain a stable posture. Defined as a perceptual-motor process, postural control involves the perception of spatial orientation that is informed by the integration of sensory information, and the selection of motor responses to maintain upright stance (Redfern et al., 2001). Multiple sources of sensory information are used to perceive one’s static and changing upright orientation in space, including the visual, vestibular, auditory, and somatosensory systems (Campos, Ramkhalawansingh, & Pichora-Fuller, 2018; Peterka, 2002). The visual system supports posture in using its unique property as a telereceptor (i.e., the ability to sense external sensory stimuli from a distance) to inform and guide spatial orientation and navigation (Bronstein & Pavlou, 2013). Moreover, dynamic visual cues (i.e., optic flow) generated by head movements provide information about self-motion through space and are thus used to inform postural adjustments
The vestibular system provides information about angular head accelerations (semicircular canals) and linear head accelerations (otolith organs: utricle and saccule), thereby providing information that can disambiguate visual self-motion perception and help guide the selection of appropriate postural responses. Auditory inputs help further optimize self-motion perception and thus consequently also support standing balance (Campos et al., 2018). Furthermore, the somatosensory system supports postural control in providing proprioceptive information about the relative position and movement of body segments, as well as tactile information about pressure and vibratory senses experienced as a result of contact between one’s feet and the support surface (Bronstein & Pavlou, 2013). Upon receiving inputs from the visual, vestibular, auditory, and somatosensory systems, the central nervous system assigns relative reliabilities to each sensory channel (Peterka, 2002). This assignment allows for sensory inputs to be weighted according to their level of reliability and subsequently integrated to inform motor output (Asslander & Peterka, 2014; Peterka, 2002).

In order to maintain one’s center of mass over their base of support, generation and coordination of multi-joint motor movements is required. Based on the integration of sensory information within the central nervous system, motor commands are sent to trunk and limb muscles to prevent loss of balance and/or to regain postural stability following a balance disturbance (Downton, 1990; Speers, Kuo, & Horak, 2002). There are three typical patterns of postural movements that are used to correct for anterior-posterior sway: an ankle strategy, a hip strategy, and a stepping strategy. The use of a particular movement pattern depends on the degree of stabilization required, with rotation about the ankle joints used for minor adjustments and strategic steps used for more significant postural perturbations (Horak, Shupert, & Mirka, 1989). For minor, routine postural adjustments, this coordinated activation of muscles supporting posture is thought to be predominantly automatic (i.e., reliant on spinal and subcortical structures) (Boisgontier et al., 2013; Stins & Beek, 2012). However, a body of evidence indicates that the maintenance of postural stability also involves cortical control (see Maki & McIlroy, 2007 for review).

One strategy for determining the extent to which cognitive resources are used to support postural control is by assessing performance differences in single-task conditions compared to dual-task conditions. Performing a postural task and a cognitive task simultaneously creates a competition scenario for cognitive resources shared by both tasks. As cognitive capacity is limited, this
competition for common cognitive resources can lead to interference in the performance of one or both tasks (Bronstein & Pavlou, 2013; Mahboobin, Loughlin, & Redfern, 2007). In using such dual-task paradigms, several studies have demonstrated that the control and regulation of posture requires attention (Kerr, Condon, & McDonald, 1985; Lajoie, Teasdale, Bard, & Fleury, 1993; Maylor & Wing, 1996; Teasdale, Bard, LaRue, & Fleury, 1993; Teasdale & Simoneau, 2001; Woollacott & Shumway-Cook, 2002). Defined as the information processing capacity of an individual (Woollacott & Shumway-Cook, 2002), attention was first implicated as a critical cognitive resource involved in postural control in a study conducted by Kerr et al. (1985). In this study, young adults were observed under single- and dual-task conditions that involved standing in a difficult position and/or completing a spatial or non-spatial memory task. Kerr et al. (1985) found that concurrent performance of the postural and spatial memory task resulted in an increased number of recall errors, but the same was not observed when the postural task was performed with the non-spatial memory task. This observed deterioration in the performance of the spatial but not the non-spatial memory task demonstrated that postural control is attentionally demanding, but that not all cognitive tasks interact with sensorimotor functioning in the same way. Further investigations have provided support for these early findings, suggesting that the maintenance of postural stability under dual-task conditions is attentionally demanding. Moreover, it has been demonstrated that such demands vary depending on cognitive task and postural task difficulty (Bernard-Demanze, Dumitrescu, Jimeno, Borel, & Lacour, 2009; Lajoie et al., 1993). Specifically, cognitive tasks that consume more available resources and postural tasks with greater intrinsic balance requirements have been demonstrated to increase the attentional demands of postural control under dual-tasking conditions (Bernard-Demanze et al., 2009; Lajoie et al., 1993; Maylor & Wing, 1996).

1.3 Postural control and aging

Research examining healthy aging has documented declines in several sensory, motor, and cognitive functions that, as described above, are critical to controlling posture. With respect to sensory function, several age-related physiological changes occur within the different sensory systems. In the vestibular system, older adults exhibit declines in hair cell populations within the canals and otolith organs, and thus typically have reduced vestibular excitability (Rosenhall, 1973). Within the auditory system, hearing is affected by age-related peripheral and cognitive changes such that older adults typically exhibit elevated tone detection thresholds, particularly in
the higher frequency range, and/or suprathreshold difficulties when auditory information is presented in noisy/multi-talker environments (Schneider, Pichora-Fuller, & Daneman, 2010). In the somatosensory system, sensation of cutaneous vibration (Birren, 1947) and joint position (Skinner, Barrack, & Cook, 1984) is reduced, thereby affecting one’s ability to sense the relative position and movement of body segments. In the visual system, loss of contrast sensitivity is common among older adults (Owsley, Sekuler, & Siemsen, 1983), as is reduction in sensitivity to low spatial frequencies (Sekuler, Hutman, & Owsley, 1980). Within the musculoskeletal system, the effects of age are reflected predominantly by changes in the characteristics of muscles. Specifically, the muscular fibers of older adults are decreased in size and number; therefore overall muscle strength is reduced (Faulkner, Larkin, Claflin, & Brooks, 2007). With age, individuals may also experience reductions in joint mobility since older adults are more likely to develop orthopedic pathologies, such as arthritis (Horak et al., 1989). In the neuromuscular system, slower neural processing among older adults can result in altered motor commands and decreased speed of muscle contractions (Borel & Alescio-Lautier, 2014). Moreover, the effects of age are reflected by changes in cognitive function, including gradual declines in processing speed (Salthouse, 2000) and declines in executive functions such as working memory (Zacks, Hasher, & Li, 2000), attention (Madden, 1990), and cognitive flexibility (Kramer, Hahn, & Gopher, 1999).

Given that postural control is supported by sensory, motor, and cognitive functions, the above-mentioned age-related changes in these functions can have detrimental effects on postural stability. For instance, deterioration of peripheral sensory structures can cause incoming sensory inputs to become dampened and/or noisy (Speers et al., 2002). This can, in turn, increase reliance on other sensory systems or, in cases where only insufficiently reliable sensory information is available, negatively affect one’s percepts of body position and orientation. Additionally, reductions in muscle strength and joint mobility can limit the performance of certain motor movements due to the restrictions imposed by the body’s biomechanics. Furthermore, changes in processing speed and availability of cognitive resources can limit central sensorimotor processes as is evidenced by an age-related decline in the efficiency of central sensory weighting (Eikema, Hatzitaki, Tzovaras, & Papaxanthis, 2012; Horak et al., 1989; Teasdale & Simoneau, 2001; Woollacott, Shumway-Cook, & Nashner, 1986). Taken together, these age-related changes can
compromise older adults’ postural stability and ultimately increase their risk of falling (Setti, Burke, Kenny, & Newell, 2011).

In fact, there is a large body of work indicating that the age-related changes in sensory, motor, and cognitive functions are reflected by an age-related change in postural control. When compared to younger adults, older adults have been observed to have increased postural sway, thereby suggesting that postural control declines with age (Maki & McIlroy, 1996; Maylor & Wing, 1996). Furthermore, postural control has been shown to shift towards more cognitively controlled processing over the lifespan (Boisgontier et al., 2013). This increase in cognitive control has been demonstrated in many studies wherein older adults require increased allocation of attentional resources to maintain postural stability (Berger & Bernard-Demanze, 2011; Bernard-Demanze et al., 2009; Brown, Shumway-Cook, & Woollacott, 1999; Dault & Frank, 2004; Granacher, Bridenbaugh, Muehlbauer, Wehrle, & Kressig, 2011; Marsh & Geel, 2000; Teasdale et al., 1993; Teasdale & Simoneau, 2001). Several explanations for this shift in the automaticity of postural control have been proposed, including age-related changes at both peripheral and central levels of processing. At the peripheral level, general degeneration of musculoskeletal, neuromuscular, and sensory systems is thought to result in compensatory increases in cognitive involvement (Boisgontier et al., 2013; Horak et al., 1989); i.e., as the quality of sensory signals and/or motor movements becomes degraded, the complexity of the postural task is increased thereby requiring additional attentional resources to maintain postural stability (Lajoie et al., 1993). At the central level, deficits in sensory weighting have been suggested to contribute to older adults’ greater reliance on cognitive processes in postural tasks (Eikema et al., 2012). Moreover, there is evidence in the cognitive ageing literature that older adults exhibit greater brain activity relative to younger adults when performing a task of equivalent cognitive load (see Grady, 2012 for review). This additional engagement of neural resources is thought to be compensatory in nature (Grady, 2012). Therefore, within the context of postural control, greater cognitive involvement among older adults can be interpreted as an attempt to resolve a mismatch between postural task demands and the availability of cognitive resources.

Further investigations examining the age-related change in postural control have considered how younger and older adults’ postural stability changes as a function of increasing sensory, motor, and cognitive challenge. Specifically, studies have examined how postural performance is
affected by systematic manipulations of visual, somatosensory, and/or cognitive load. For instance, in examining age-related differences in postural sway under altered sensory conditions, Teasdale, Stelmach, and Breunig (1991) measured participants’ postural performance while standing on a firm support surface compared to a compliant foam surface. In having participants stand on a compliant surface, Teasdale et al. (1991) altered the reliability of somatosensory contributions to postural control, thus forcing participants to rely more heavily on visual and/or vestibular information (Straube, Botzel, Hawken, Paulus, & Brandt, 1988). Despite increasing postural sway among younger and older adults, this increase in somatosensory challenge was not found to be sensitive to age-related differences in postural control when applied on its own (Teasdale et al., 1991). However, when visual and somatosensory challenge were both increased (i.e., foam surface with eyes closed), Teasdale et al. (1991) observed greater postural sway among older adults compared to younger adults. These findings align with the belief that postural tasks involving two unreliable sensory inputs have greater sensitivity to detecting differences between younger and older adults (Woollacott et al., 1986).

When cognitive load is increased, such postural tasks can be highly sensitive to age-related differences in postural control. This has been demonstrated in dual-task studies wherein the addition of a cognitive task and the simultaneous manipulation of visual and somatosensory information has exposed greater postural performance decrements among older adults compared to younger adults (Doumas et al., 2008; Redfern et al., 2001; Shumway-Cook & Woollacott, 2000). Furthermore, when cognitive load is independently increased by the introduction of a more cognitively demanding task, older adults have been shown to exhibit similar declines in postural performance (Bernard-Demanze et al., 2009). Taken together, these findings suggest that increases in postural task difficulty introduced via manipulations of sensory and/or cognitive load can improve the sensitivity of postural paradigms to detect differences between younger and older adults.

Therefore, in the current study, younger and older adults performed a postural task (namely quiet standing) under various different degrees of visual, somatosensory, and cognitive challenge. This was accomplished using a dual-task paradigm involving standing (postural task) while listening (cognitive task) under firm and compliant standing conditions, with and without visuals (i.e., eyes open and closed). This study looked to examine how postural and cognitive performance was affected by these manipulations under more realistic, real-world conditions. Specifically,
virtual reality technologies were used to ensure that the testing environment was not only safe and controlled, but also ecologically valid and realistic. Notably, the introduction of a virtual environment allowed for the complexities of everyday visual settings to be more accurately reflected. This was of particular importance for the eyes open conditions, in that more complex visual surrounds may allow for sensory augmentation within postural tasks, thereby facilitating improvements in postural performance. On the other hand, as discussed below, complex visual environments could negatively affect cognitive performance by means of sensory interference and/or distraction.

1.4 Auditory processing and aging

The effects of age on postural and cognitive performance in the context of dual-task conditions have been well documented (see Boisgontier et al., 2013 for review). However, the types of cognitive tasks that have been used in previous studies are not necessarily representative of the typical challenges faced in everyday environments. Commonly used cognitive tasks have included working memory (e.g., Doumas et al., 2008), visual/auditory reaction time (e.g., Redfern et al., 2001; Shumway-Cook & Woollacott, 2000), mental arithmetic (e.g., Brown et al., 1999; Kerr et al., 1985), and visuospatial memory tasks (e.g., Andersson, Yardley, & Luxon, 1998). When wanting to introduce general cognitive load and/or tap into cognitive processes that are involved in postural control (i.e., processing of visuospatial information), the above-mentioned tasks serve as valuable tools. However, their abstract nature is limiting in that it does not reflect the everyday cognitive tasks that are typically paired with standing (e.g., conversing). As such, previous postural dual-task studies have made it difficult to evaluate how performance of complex, daily activities, such as standing while listening, differs between younger and older adults. In order to address this limitation imposed by previously used cognitive tasks, this study introduced a real-world cognitive challenge more frequently associated with sensorimotor functioning – effortful listening.

It is well established that older adults have greater speech understanding difficulties than younger adults, particularly in noisy communication environments (Martin & Jerger, 2005). In fact, this age-related difference has been shown to exist even among older adults with healthy peripheral hearing (i.e., pure-tone average thresholds within normal clinical limits) (CHABA, 1988). For those with normal peripheral hearing abilities, comprehension difficulties may be
explained by age-related declines in suprathreshold auditory processing and/or cognition (CHABA, 1988). Defined as the mechanisms and processes that underlie various aspects of audition (specifically, sound localization and lateralization, auditory discrimination and recognition, temporal processing, and auditory performance with competing/degraded acoustic signals), auditory processing is what allows for the perception of information sensed by one’s ears (Catts et al., 1996). Therefore, declines in auditory processing can adversely affect communication. Specifically, age-related declines in suprathreshold auditory processing (e.g., temporal processing) can result in the need for greater deliberate allocation of resources to the act of listening, thereby causing listening to become more effortful (Pichora-Fuller et al., 2016). This increase in listening effort suggests that more cognitive resources need to be expended in order to compensate for degraded auditory inputs; perhaps at the expense of other concurrent tasks (e.g., mobility-related tasks).

Resulting in a similar shift towards more cognitively controlled processing, acoustically adverse (e.g., noisy) and informationally complex (e.g., multitasking) situations can also result in effortful listening (Pichora-Fuller et al., 2016; Schneider et al., 2010). For instance, when background noise and/or simultaneous competing auditory signals are presented to listeners, greater mental effort is required to parse relevant auditory information from irrelevant auditory information. Similarly, when listening in visually complex environments, individuals must expend additional cognitive resources to attend to relevant auditory information and inhibit irrelevant visual information (i.e., avoid visual distraction) (Guerreiro, Murphy, & Van Gerven, 2013). That said, compared to younger adults, older adults exhibit greater processing of irrelevant visual information when performing auditory tasks (Murphy, Maec, Howell, & Bailey, 2004), which is likely related to their observed declines in auditory task performance when exposed to visual distraction (Guerreiro et al., 2013; Guerreiro & Van Gerven, 2011). These findings suggest that listening in visually complex environments may be particularly effortful for older adults if surrounding visual information is irrelevant. Another complex situation in which older adults may experience more effortful listening is when listening is performed under dual-tasking conditions. For instance, when listening is performed simultaneously with a postural task such as standing or walking, cognitive resources must be appropriately allocated to relevant auditory and motor inputs. However, there is evidence to suggest that auditory functioning and postural stability may compete for cognitive resources as
one gets older (Li & Lindenberger, 2002). As such, older adults may find that they are limited in their ability to effectively attend to all necessary inputs when tasked with listening while standing/walking. Consequently, their listening and/or postural performance may be compromised as a result of this competition for common cognitive resources. Taken together, increased effort is likely required when older adults are tasked with listening in noisy/multi-talker environments, in visually complex environments, or while performing a concurrent postural task. However, less is understood about the relative and/or interactive effects of these different challenges on older adults’ auditory perception and performance.

Therefore, the current study introduced a task that was better able to address these potential effects. Specifically, a variation of the Dichotic Digits Test (DDT; Musiek, 1983) that involved the presentation of digits through loudspeakers rather than through headphones was used as the cognitive task within the study’s dual-task paradigm. Involving the simultaneous presentation of spoken digits and requiring listeners to repeat back the digits in no particular order, the DDT challenges auditory processing and cognitive functioning (Fischer et al., 2017). Moreover, the variation used in the current study better reflects typical challenges experienced in real-world communication environments (i.e., multi-talker babble), thereby providing valuable insight into how individuals cope when listening in more ecologically valid settings. Furthermore, using a variation of the DDT within the context of a cognitive-motor dual-task served as an opportunity to extend a growing body of research looking at the association between aging, audition, and postural control. Existing evidence suggests that older adults with age-related hearing loss are at greater risk of falling due to reduced postural control (see Agmon, Lavie, & Doumas, 2017; Campos et al., 2018 for reviews). However, little is known about whether, and to what degree, this association is related to age-related deterioration of suprathreshold auditory processes. As such, introducing a task thought to challenge these processes within the context of a postural dual-task paradigm allowed for this study to more explicitly address the relation between auditory processing and postural control in younger and older adults. Moreover, as described further below, the inclusion of a variation of the DDT was also partly motivated by the DDT’s ability to differentiate between cognitively healthy individuals and individuals at potential risk of cognitive impairment/decline (i.e., those with subjective cognitive decline) (Idrizbegovic et al., 2011).
1.5 Subjective cognitive decline

In addition to evaluating the effects of “normal” aging on listening while standing, this study also considered how performance on this complex, everyday task might be affected in those at potential risk of cognitive impairment/decline. As previously discussed, postural control is vulnerable to the effects of aging due to age-related changes in sensory, motor, and cognitive functioning. However, when aging is associated with non-normative changes in cognition, postural control can be further compromised. For instance, compared to individuals with normal cognition, individuals with mild cognitive impairment (MCI) and Alzheimer’s disease (AD) exhibit poorer postural stability (Shin, Han, Jung, Kim, & Fregni, 2011; Tangen, Engedal, Bergland, Moger, & Mengshoel, 2014). The extent of declines in postural control is thought to be associated with the degree of cognitive impairment, such that individuals diagnosed with AD typically experience greater postural difficulties than individuals diagnosed with MCI (Tangen et al., 2014). Interestingly, individuals with MCI and AD have also been shown to experience declines within their speech understanding abilities, as evidenced by deficits in auditory processing (Idrizbegovic et al., 2011). Specifically, individuals with AD, and to a lesser extent individuals with MCI, have been found to have central auditory dysfunction as measured by central auditory tests (e.g., the DDT) (Gates, Anderson, Feeney, McCurry, & Larson, 2008; Gates, Anderson, McCurry, Feeney, & Larson, 2011; Idrizbegovic et al., 2011).

Motivated by these findings and their relevance to the dual-task paradigm used in this study, I looked to explore the functional abilities of a considerably less studied group of individuals who are thought be at elevated risk of developing dementia; specifically, older adults with subjective cognitive decline (SCD). Described by Reisberg et al. (2008) as being the stage of decline when “the patient knows but the doctor doesn’t know” (p. 105), SCD is characterized by subjectively perceived cognitive decline in the absence of any measurable neuropsychological deficits using standard tests of cognitive functioning (Jessen et al., 2014). Over the past decade there has been significant growth in research looking at what these subjective perceptions of cognitive decline mean (see Rabin et al., 2017 for review). Considering questions like “What is the cause of these subjective expressions of cognitive change?” and “Where, if at all, do these individuals fall within the objective continuum of cognitive decline?”, this research has brought widespread attention to SCD and its potential role as a marker of preclinical AD (Rabin et al., 2017). With growing evidence that older adults presenting with SCD have an increased likelihood of
biomarker abnormalities that are consistent with AD pathology, SCD is increasingly thought to be indicative of a greater risk of future cognitive decline and dementia (Jessen et al., 2014). As individuals with SCD may in fact be in the earliest stages of non-normative cognitive decline (Rabin et al., 2017), development of a measure that is sensitive to the changes experienced by individuals with SCD at very early stages is desirable. Therefore, in using the current study’s dual-task paradigm to more accurately reflect real-world challenges, I evaluated whether older adults’ postural and/or cognitive performance was affected by their subjective cognitive status.

However, being a subjective measure, SCD is based on self-report and is therefore difficult to assess in an objective fashion that ensures internal consistency (Ávila-Villanueva & Fernández-Blázquez, 2017). Additionally, it is possible that expressions of decline may not always be indicative of preclinical AD, as there are many potential reasons for which one may present with SCD (Cheng, Chen, & Chiu, 2017; Rabin et al., 2017). For instance, certain individuals, particularly those who fall prey to negative age stereotypes and thus hold negative views of aging or who have a known family history of AD, may be hypervigilant about their health and/or overly concerned about developing dementia. Consequently, such individuals may believe that they are experiencing atypical declines in cognition, when in reality their perceived ‘declines’ are typical of normal healthy aging. Commonly referred to as the “worried well”, this group of individuals demonstrates why expressions of SCD cannot alone serve as a reliable indicator of one’s risk of future cognitive decline. That said, if paired with an objective measure with sufficient sensitivity to identify early atypical changes in cognition, SCD could be a potentially valuable target for early interventions aimed at preserving cognition in its most functional form (Jenkins, Tales, Tree, & Bayer, 2015; Jessen et al., 2014; Rabin et al., 2017; Reisberg et al., 2008).

As the population ages and the number of people affected by dementia grows, the need for such a measure is made apparent by the increasing interest placed on detecting and in turn delaying non-normative cognitive decline at the earliest possible stage (Bernier et al., 2017). The need for early identification is thought to be of particular importance for AD, as not only is it the most common cause of dementia (Bernier et al., 2017), but also the pathophysiological process of AD is thought to begin years prior to any objectively measureable cognitive decline made evident using current diagnostic methods (Cheng et al., 2017; Lucas et al., 2016). Therefore, in order to effectively implement interventions to prevent or delay disease-associated decline, it is essential
that identification of individuals at risk of developing AD occurs at very early stages of disease progression. Current measures may lack sensitivity because they target specific cognitive processes and are not reflective of everyday challenges. However, tasks that simultaneously challenge sensory, motor, and cognitive processes, particularly those that are reflective of functional, real-world tasks, may provide greater sensitivity to mild impairments given that sensory and motor changes have also been evidenced to precede dementia (Albers et al., 2015; Livingston et al., 2017). As such, the dual-task paradigm used in this study could potentially serve as a valuable tool if found to be sufficiently sensitive to performance differences suggestive of individuals with SCD experiencing greater cognitive difficulties than individuals without SCD. More generally, it could help deepen our understanding of how everyday experiences of individuals with SCD may or may not differ from those of “healthy” older adults.

1.6 Rationale and hypotheses for the current study

Postural stability is central to the performance of everyday mobility-related tasks. There is evidence to suggest that, due to changes in underlying sensory, motor, and cognitive processes, postural control is vulnerable to the effects of aging. It has also been demonstrated that auditory processing declines with age, as evidenced by older adults’ greater speech understanding difficulties in noise than younger adults (Martin & Jerger, 2005). However, little consideration has been given to the combined effects of these age-related changes in postural control and auditory processing, particularly within the context of sensory conditions and cognitive challenges that are more reflective of everyday life. In a similar vein, previous postural dual-task studies have lacked ecological validity in that they have been conducted in predominantly artificial testing environments and have used relatively abstract cognitive tasks that are not representative of typical challenges faced in real-world environments.

Therefore, the first study objective was to identify the age-related differences in performing a postural task while simultaneously performing an auditory processing task under more realistic conditions. This was achieved by using a dual-task paradigm reflective of everyday real-world challenges in which postural load, listening load, and visual load were manipulated. The postural task involved either sitting, standing on a firm surface, or standing on a compliant surface, while the listening task (i.e., the DDT presented over loudspeakers) included three listening loads – no load, low load (simultaneous presentation of a digit pair), and high load (sequential presentation
of two simultaneous digit pairs). The postural task and listening task were then further manipulated by introducing or removing visuals (i.e., eyes open vs. closed) within a virtual reality environment. Given previous findings indicating age-related changes in postural control and auditory processing, I hypothesized that older adults would exhibit greater decrements in postural control and listening response accuracy than younger adults, particularly as listening load, visual load, and postural load increased.

The second study objective was to identify any differences in performance between older adults with and without SCD using the same task and experimental manipulations. With evidence to suggest that individuals with SCD may be in the earliest stages of cognitive decline and therefore may exhibit sensory, motor, and/or cognitive changes, I hypothesized that older adults with SCD would exhibit greater decrements in postural control and listening response accuracy than older adults without SCD. Further, I hypothesized that this difference would become larger as listening load, visual load, and postural load increased.

2 Methods

2.1 Participants

The participants included sixteen younger adults (YA group; $M = 25.38, SD = 3.07; 9$ males), fourteen older adults with self-identified normal cognition (OA group; $M = 66.36, SD = 4.80; 5$ males), and sixteen older adults with SCD (SCD group; $M = 70.63, SD = 6.96; 3$ males). Older adults were included in the SCD group if they answered ‘yes’ when asked “Do you feel like your memory or thinking is becoming worse?”, while those who answered ‘no’ to this question were included in the OA group.

Participants were recruited through advertisements in “Metro” a Toronto-based daily newspaper and the University of Toronto’s Senior Alumni Association newsletters, as well as by recruitment flyers distributed throughout the local Toronto community. All prospective participants were screened over the phone for eligibility. Those who were fluent in English and reported having normal or corrected-to-normal vision, unimpaired mobility, and no prior history of stroke, neurological disease, MCI, and/or dementia were brought into the lab to complete audiometric testing. Audiometry was used to ensure that all participants’ pure-tone air conduction thresholds were symmetrical (inter-aural difference < 15 dB HL) and normal (better
ear pure-tone average ≤ 25 dB HL) for test frequencies from 0.5 to 3 kHz. Younger adult participants completed audiometry immediately prior to the experimental session, while both groups of older adult participants (OA and SCD) completed audiometry as part of a larger battery of screening and baseline assessments (described in section 2.2). During this dedicated assessment session, older adults were also screened for cognitive impairment using the Montreal Cognitive Assessment (MoCA). For those in the OA group, a MoCA cutoff score of ≥ 26 out of 30 was used to define eligibility. However, for those in the SCD group, eligibility was determined solely using the results of the pure-tone audiometry and no MoCA cutoff point was used for inclusion. Therefore, two potential OA participants who scored below the MoCA cutoff score were subsequently excluded from the experimental session, while five SCD participants, who later completed the experimental session, scored below the MoCA cutoff score. Out of the 55 prospective older adult participants who completed the assessment session, only 30 (14 OA and 16 SCD) met their respective inclusion criteria and/or were available to participate in the experimental session. All participants were compensated at a rate of $10 per hour for their time and informed consent was obtained prior to participation. The protocol for the study was approved by the University Health Network’s Research Ethics Board.

2.2 Assessment session

The assessment session was used to screen for eligibility and characterize participants, as well as to understand potential associations with experimental outcomes. It consisted of a series of hearing, vision, balance, and cognitive tests (each described below in sections 2.2.1 – 2.2.4). The session was completed by all older adult participants (OA and SCD), while only a portion of it was completed by younger adult participants (specifically, audiometry, history questionnaire, and visual acuity test). During the assessment session, each participant completed a history questionnaire that was used to gather detailed information about their demographic and health history. Of the tests described below, only the results from the audiogram and MoCA were used to determine eligibility to participate in the experimental session, while the other assessments contributed to the characterization of participants’ functional status (see Table 1 for a summary of demographics and assessment session outcome measures for all three experimental participant groups).
2.2.1 Hearing

Participants’ peripheral and central hearing was tested using a series of assessments, all of which were conducted in a double-walled ANSI standard sound booth (Industrial Acoustics Company, Inc., New York, NY). Pure-tone audiometry, the Dichotic Digits Test (DDT; Musiek, 1983), and the Coordinate Response Measure (CRM; Bolia, Nelson, Ericson, & Simpson, 2000) were performed using a Grason-Stadler 61 (GSI-61; Grason-Stadler Inc., Eden Prairie, MN) audiometer and Telephonics TDH-50P (Telephonics Corporation, Farmindale, NY) headphones, while the Digit Triplet Test (DTT; Ellaham, Giguère, Lagacé, & Pichora-Fuller, 2016) was conducted on a laptop with Telephonics TDH-50P headphones. Audiometry was used to assess participants’ pure-tone thresholds and served as an exclusion criterion for all potential participants. The DDT – a test in which double digit pairs are presented dichotically – was used to assess participants’ auditory processing abilities. The CRM and DTT both served as assessments of word recognition accuracy. The CRM measured speech intelligibility in a multi-talker communication environment using spoken phrases consisting of a call sign and a colour-number combination as the stimuli, while the DTT served as an easier alternative to the CRM and assessed speech recognition ability in noise using spoken digits as the stimuli.

In addition to using the DDT, CRM, and DTT as baseline measures within “ideal listening conditions” (i.e., administered through headphones in a sound booth), I was interested in determining whether one was more sensitive to differentiating between OA and SCD participants, and could therefore be a more suitable choice for use during the experimental dual-task. However, as none of the measures differentiated between the groups (see Table 1), I selected the DDT since it is a) known to be affected by objectively diagnosed cognitive decline (Idrizbegovic et al., 2011) and b) easily manipulated in terms of task difficulty (Strouse, & Wilson, 1999).

2.2.2 Vision

Participants’ vision was assessed using the Early Treatment Diabetic Retinopathy Study (ETDRS) visual acuity test (Ferris, Kassoff, Bresnick, & Bailey, 1982). While this gold standard measurement of visual acuity was not used as an eligibility criteria, it provided confirmation that, according to the International Council of Ophthalmology (2002), all participants’ vision fell within the normal to near-normal range (-0.2 to 0.5 logMAR units).
2.2.3 Balance and mobility

The Timed Up and Go (TUG) test (Podsiadlo & Richardson, 1991) served as a measure of functional mobility in assessing how quickly participants could stand up from a seated position, walk 3 m, turn, walk back, and sit down. Scoring for the TUG was calculated by averaging the time of two TUG test trials. Scores of $\geq 13.5$ seconds are associated with a greater risk of falls (Shumway-Cook, Brauer, & Woollacott, 2000); however, all participants scored below this falls risk cutoff point.

2.2.4 Cognition

A series of cognitive tests were conducted to characterize participants’ cognitive abilities. This included the MoCA (Nasreddine et al., 2005), the Wechsler Adult Intelligence Scale III (WAIS-III) Digit Span test (Wechsler, 1997), the WAIS-III Digit-Symbol Coding test (Wechsler, 1997), the Stroop test (Stroop, 1935), the Trail Making Test (TMT; Reitan, 1955), and the Rey Auditory Verbal Learning Test (RAVLT; Rey, 1964; Schmidt, 1996). The MoCA served as a global screening tool for mild cognitive impairment and was used as an exclusion criterion for OA but not SCD participants. The WAIS-III Digit Span and Digit-Symbol Coding tests were used to assess participants’ working memory and processing speed, respectively. The Digit Span test was scored out of 30, while scoring for the Digit-Symbol Coding test corresponded to the number of correctly completed symbols in 120 seconds. The Stroop test served as a measure of cognitive interference and was scored by subtracting the completion time of the ‘colour’ form from that of the ‘colour-word’ form. Participants’ cognitive flexibility was further assessed using the TMT in which lower scores on Trails A and B were reflective of greater flexibility. Lastly, participants performed the RAVLT – an assessment of verbal learning and memory that includes both immediate and 20-min delayed recall of a word list. Scoring for the RAVLT was out of 15 for immediate and delayed recall.
Table 1. *Summary of demographics and assessment session outcome measures for all three experimental participant groups*

<table>
<thead>
<tr>
<th>Variable</th>
<th>YA Group (N = 16)</th>
<th>OA Group (N = 14)</th>
<th>SCD Group (N = 16)</th>
<th>p-values ¹</th>
</tr>
</thead>
<tbody>
<tr>
<td>Demographics</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Age (years)</td>
<td>25.38</td>
<td>66.36</td>
<td>70.63</td>
<td>0.06</td>
</tr>
<tr>
<td>Education (years)</td>
<td>17.38</td>
<td>15.43</td>
<td>16.50</td>
<td>0.32</td>
</tr>
<tr>
<td>Hearing</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Better ear PTA (dB HL)</td>
<td>1.95</td>
<td>10.18</td>
<td>14.30</td>
<td>0.09</td>
</tr>
<tr>
<td>Dichotic Digits Test score (%)</td>
<td>–</td>
<td>94.43</td>
<td>90.81</td>
<td>0.19</td>
</tr>
<tr>
<td>Coordinate Response Measure (%)</td>
<td>–</td>
<td>93.57</td>
<td>95.31</td>
<td>0.56</td>
</tr>
<tr>
<td>Digit Triplets Test score (dB SNR) ³</td>
<td>–</td>
<td>-10.14</td>
<td>-10.01</td>
<td>0.66</td>
</tr>
<tr>
<td>Hearing</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Vision</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Better eye ETDRS score</td>
<td>–</td>
<td>0.08</td>
<td>0.13</td>
<td>0.43</td>
</tr>
<tr>
<td>Balance and Mobility</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>TUG time (sec)</td>
<td>–</td>
<td>9.25</td>
<td>8.34</td>
<td>0.11</td>
</tr>
<tr>
<td>Cognition</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>MoCA score</td>
<td>–</td>
<td>28.21</td>
<td>26.88</td>
<td>0.04</td>
</tr>
<tr>
<td>Digit Span total score</td>
<td>–</td>
<td>19.71</td>
<td>19.75</td>
<td>0.98</td>
</tr>
<tr>
<td>Digit-Symbol Coding score</td>
<td>–</td>
<td>66.43</td>
<td>68.50</td>
<td>0.64</td>
</tr>
<tr>
<td>Stroop test difference score (sec)</td>
<td>–</td>
<td>50.25</td>
<td>62.75</td>
<td>0.05</td>
</tr>
<tr>
<td>TMT Trail A score (sec)</td>
<td>–</td>
<td>36.92</td>
<td>37.60</td>
<td>0.88</td>
</tr>
<tr>
<td>TMT Trail B score (sec)</td>
<td>–</td>
<td>68.69</td>
<td>86.04</td>
<td>0.23</td>
</tr>
<tr>
<td>RAVLT immediate recall</td>
<td>–</td>
<td>11.79</td>
<td>9.25</td>
<td>0.02</td>
</tr>
<tr>
<td>RAVLT delayed recall</td>
<td>–</td>
<td>11.57</td>
<td>9.00</td>
<td>0.03</td>
</tr>
</tbody>
</table>

Notes: significance level of $p < 0.5$; table only includes data of participants who completed the experimental session

¹ t tests comparing OA and SCD values
² PTA = pure-tone average of thresholds at 0.5, 1, 2, and 3 kHz
³ Adaptive speech reception threshold (SRT)
⁴ DTT Descriptive statistics for 15 of 16 SCD participants
⁵ For corrected vision in logMAR units
⁶ Adjusted for years of education
2.3 Experimental session

2.3.1 Testing environment

The experimental session was conducted in StreetLab, a virtual reality laboratory within Toronto Rehabilitation Institute’s Challenging Environment Assessment Laboratory (see Figure 1). The lab is outfitted with a 240° horizontal x 110° vertical curved projection screen combined with surround sound loudspeakers and an AMTI (Advanced Mechanical Technology, Inc., Watertown, MA) BP12001200-2000 strain gage force plate. In this study, the virtual environment used was a high-resolution static simulation of downtown Toronto. The laboratory’s ambient noise was measured with a Galaxy Audio CM-140 sound level meter and averaged 52 dB SPL.

![Figure 1. StreetLab shown with a participant standing on the force plate.](image)

2.3.2 Experimental listening task and manipulations

A variation of the DDT served as the listening task in the experimental session. It involved the presentation of digits from two loudspeakers positioned 2.14 m away from participants (90° to their left and right) and tasked participants with repeating the digits back in no particular order. Three versions of the DDT stimuli were used: a sequential presentation of a digit pair, a simultaneous presentation of a digit pair, and a sequential presentation of two simultaneous digit pairs. In all versions, numbers ranging from one to nine (excluding seven) were presented randomly.
In the *sequential digit pair* version, a trial consisted of the presentation of two digits – one digit from the left loudspeaker and a different digit from the right loudspeaker. Digits were presented sequentially with a 0.25 second silence between each digit. This sequential digit pair version was used solely for practice and threshold testing which helped ensure that participants a) understood the task and were familiar with the stimuli, b) were able to repeat the digits back without interference from a competing talker, and c) were able to adequately hear the stimuli (see Procedures below). As in the sequential digit pair version, the *simultaneous digit pair* version involved the presentation of two digits per trial (one from each loudspeaker). However, instead of being presented sequentially, the digits were presented simultaneously with no time separation between each digit. This simultaneous digit pair version served as the ‘low load’ listening condition within the testing phase. Lastly, in the *two digit pairs* version, a trial involved two of the simultaneous digit pair presentations separated by one second. Therefore, the two digit pairs version consisted of two pairs of digits presented one second apart (i.e., four digits presented per trial). Essentially, it consisted of two sequentially presented simultaneous pairs. This two digit pairs version of the DDT served as the ‘high load’ listening condition within the testing phase. A ‘no load’ condition, in which no digits were presented, was also used within the testing phase as it served as the listening task control. During this condition, participants did not perform the DDT, but rather repeated a ‘dummy’ word four times per trial (see Procedures below).

In all versions of the listening task, participants were instructed to repeat the digits back in any order and their response was recorded on a tablet computer. If ever unsure of a presented digit, participants were instructed to take their best guess and compliance was ensured such that a complete response was given for every trial. The DDT test materials were obtained from a CD audio recording in which all recorded digits were naturally spoken by a single male speaker (Musiek, 1983). In order to ensure consistency among participants, pre-set lists of the recorded digits were created and used for the practice, threshold, and testing phases (as described above).

### 2.3.3 Experimental postural task and manipulations

While performing the listening task, participants simultaneously performed a postural task on the force plate. The postural task involved either sitting on a chair, standing directly on the force plate (firm surface), or standing on a piece of high-density foam placed on top of the force plate (compliant surface). Sitting served as the ‘no load’ postural condition (i.e., the postural task
control), while firm surface standing served as the ‘low load’ postural condition and compliant surface standing served as the ‘high load’ postural condition.

During standing, participants were instructed to stand with their feet shoulder-width apart and maintain a comfortable upright, forward-facing posture with their arms by their side. Force plate data was collected and recorded during both standing conditions (firm and compliant), and the signals were amplified by an AMTI MSA-6 MiniAmp strain gage amplifier. The gains for the forces (x, y, z) were set to 2000 and the gains for the moments (x, y, z) were set to 4000. The excitation voltages were set to 5 VDC for the forces and 10 VDC for the moments. The posturography data was collected at a sampling rate of 1000 Hz and was recorded with timestamps indicating the onset and completion of each simultaneously performed listening task trial. This allowed for the data recorded during listening task trials to be considered independently of that recorded outside of trials. Only the data corresponding to listening trials was used. In Matlab, the data was subjected to a second-order dual-pass Butterworth filter with a 6 Hz cutoff frequency to filter out high frequency noise. Center of pressure (COP) path length was then derived for each trial.

2.3.4 Visual manipulations

The listening task and postural task were further manipulated by altering the availability of visual information. Participants were asked to either wear or not wear a blindfold (eyes open vs. closed) while surrounded by a static simulation of downtown Toronto in StreetLab. During eyes open conditions, participants wore their contacts/glasses as prescribed and were instructed to maintain focus on the visual scene displayed directly in front of them.

2.4 Procedure

Older adult participants (OA and SCD) began by completing the approximately 120 minute long assessment session. This session was conducted on a separate day in advance of the experimental session as it was used to determine eligibility and characterize participants. Younger adult participants performed audiometric testing immediately prior to their experimental session to ensure the minimum hearing criteria was met, and they completed the history questionnaire and the ETDRS visual acuity test.
Prior to entering StreetLab, participants were instructed to remove their shoes and were outfitted with a harness. The harness system was used simply as a safety precaution and great care was taken to ensure that it did not provide participants with additional support during the postural tasks.

Participants began the experimental session by completing a practice phase, which helped familiarize them with the task instructions and stimuli. It involved performing three practice listening task conditions while standing directly on the force plate (firm surface) with their eyes open. The conditions were performed in the following order: sequential digit pair, simultaneous digit pair, sequential presentation of two simultaneous digit pairs. Participants were required to complete a minimum of 5 successful trials and/or up to 10 trials per condition, and the digits were presented at 70 dB SPL to ensure that the stimulus was audible for all participants.

In order to determine an appropriate presentation level for the auditory stimulus during testing, participants completed a threshold test. This was done using the sequential digit pair version of the listening task as the simplicity of this version helped ensure that participants’ performance reflected the audibility of the stimuli rather than the difficulty of the task. Participants were instructed to maintain the same posture as in the practice conditions. Beginning at a presentation level just above the laboratory’s ambient noise level (52 dB SPL), participants performed 5 trials of the sequential digit pair listening task at each of the presentations levels, which increased in intensity until they correctly completed at least 4 out of 5 trials at one of the presentation levels. The presentation level to be used for testing was then calculated by adding 10 dB to the level at which the participant successfully completed at least 4 out of 5 trials. This ensured that participants’ listening task performance during the testing phase was not affected by their ability to hear the auditory stimulus.

During the testing phase, participants completed a total of 16 different conditions comprising of various combinations of the following manipulations: posture (sitting vs. standing firm vs. standing compliant), vision (eyes open vs. closed), listening (no vs. low vs. high listening load) (see Figure 2). Based on the recommendations of Carpenter, Frank, Winter, and Peysar (2001), each condition was limited to approximately 60 seconds of standing (posturography data) to minimize any effects due to fatigue while optimizing the stability and reliability of COP path.
length measures during quiet stance. The number of listening task trials that could be completed within approximately 60 seconds amounted to six listening task trials per postural condition.

**Figure 2.** Flowchart illustrating the experimental session design where red represents postural load, blue represents visual load, and green represents listening load. There were 6 trials per condition (i.e., per green box).

The physical act of speaking in and of itself can affect postural control (Dault, Yardley, & Frank, 2003). Therefore, a ‘dummy’ word was used during the ‘no load’ and ‘low load’ listening conditions in order to control for any possible effects of speaking on participants’ posture. For the ‘no load’ conditions, participants were instructed to say “beep, beep, beep, beep” when prompted by a brief tone presented from both left and right loudspeakers. For the ‘low load’ conditions, participants were instructed to say “beep, beep” following their repetition of the two digits that were presented. This helped to ensure that the amount of speaking in each listening task trial response was equal across all listening conditions.

The condition order was counterbalanced with respect to listening load (low vs. high) and postural load (sitting vs. standing). All other variables were ordered according to difficulty level.
(i.e., eyes open then closed, and firm standing surface then compliant). Breaks were provided as needed between conditions, and all participants were debriefed and compensated following completion of both the assessment and experimental session.

2.5 Design

A 3 x 2 x 2 x 3 mixed-factorial design was used. The independent variables for the examination of postural control included group (YA vs. OA vs. SCD), visual load (eyes open vs. closed), postural load (standing firm surface vs. compliant surface), and listening load (no load vs. low load vs. high load). The independent variables for the examination of listening task performance included group (YA vs. OA vs. SCD), visual load (eyes open vs. closed), listening load (low load vs. high load), and postural load (sitting vs. standing firm surface vs. standing compliant surface). The dependent variables included postural control and listening task performance, which were quantified as COP path length (cm) and response accuracy (percentage) respectively. For both dependent variables, group served as a between-subject factor while visual load, postural load, and listening load served as within-subject factors. A significance level of $p < 0.5$ was used in all analyses and violations of sphericity were accounted for using the Greenhouse-Geisser (Greenhouse & Geisser, 1959) correction.

3 Results

For both dependent variables, a 3 x 2 x 2 x 3 mixed-factorial ANOVA was conducted. The levels of two independent variables (postural load and listening load) differed between dependent variables, such that postural control was analyzed using a 3 (group) x 2 (visual load) x 2 (postural load) x 3 (listening load) mixed-factorial ANOVA while listening task performance was analyzed using a 3 (group) x 2 (visual load) x 2 (listening load) x 3 (postural load) mixed-factorial ANOVA.

3.1 Postural control

COP path length (cm), defined as the absolute length of COP path movements throughout a testing period, was used to quantify and analyze postural control (see Figure 3 for example). Expressed as a mean measurement for each condition, COP path length was calculated by averaging across the path length measurements from the six trials within one condition. Longer COP path lengths equated to greater postural sway (i.e., less stable posture).
The omnibus mixed-factorial ANOVA showed a significant main effect of group ($F(2, 43) = 17.52, p < .001$). Given the hypothesized effects unique to 1) healthy aging and 2) subjective changes in cognition, this warranted two separate analyses. Specifically, one ANOVA was conducted to compare the YA and OA groups (effect of aging) and a separate ANOVA was conducted to compare the OA and SCD groups (effect of subjective cognitive ability); each ANOVA consisting of a 2 (group) x 2 (visual load) x 2 (postural load) x 3 (listening load) mixed-factorial design. Significant main and interaction effects were subsequently subjected to post-hoc analyses consisting of multiple comparisons using the Bonferroni correction.

### 3.1.1 Younger versus older adults

The ANOVA showed a significant main effect of group ($F(1, 28) = 41.11, p < .001$) with the OA group exhibiting longer COP path lengths than the YA group. There were also significant main effects of postural load ($F(1, 28) = 290.90, p < .001$) and visual load ($F(1, 28) = 156.88, p < .001$) in which COP path length was longer during standing on a compliant surface compared to a firm surface and with eyes closed compared to eyes open. Lastly, there was a significant main effect of listening load ($F(1.52, 42.65) = 46.63, p < .001$) for which the post-hoc tests showed that COP path length was longer during high load listening conditions than during low load ($p < .05$) and no load ($p < .01$) listening conditions. However, there was no observed difference between low load and no load conditions.
The ANOVA also showed significant interaction effects between the between-subject factor group and the three within-subject factors – listening load, visual load, and postural load. There was a significant two-way interaction effect between group and listening load \((F(1.52, 42.65) = 6.54, p < .01)\) for which two one-way ANOVAs were conducted to consider the YA and OA groups independently. The post-hoc tests indicated that while the OA group exhibited comparable COP path length across all listening load conditions \((p > .05\) for all comparisons), the YA group exhibited longer COP path lengths during high load listening conditions than during both low load \((p < .05)\) and no load \((p < .05)\) listening conditions (see Figure 4).

![Figure 4](image.png)

**Figure 4.** Mean COP path length (cm) of younger versus older adults across the three listening load conditions collapsed across postural load and visual load. Error bars represent ± SE.

The two-way interaction effect between group and visual load was also significant \((F(1, 28) = 16.48, p < .001)\). The post-hoc tests indicated that the OA group had longer COP path lengths than the YA group during both eyes open \((p < .001)\) and eyes closed \((p < .001)\) conditions, however the magnitude of this age group difference was greater in eyes closed conditions (YA: \(M = 11.49\); OA: \(M = 20.14\)) compared to eyes open conditions (YA: \(M = 7.72\); OA: \(M = 12.75\)). Lastly, there was a significant two-way interaction effect between group and postural load \((F(1, 28) = 64.91, p < .001)\). The post-hoc tests showed that although the OA group had
longer COP path lengths than the YA group during standing on both firm \((p < .001)\) and compliant \((p < .001)\) surfaces, the magnitude of the age group difference was greater when standing on a compliant surface \((\text{YA}: M = 12.72; \text{OA}: M = 25.15)\) compared to when standing a firm surface \((\text{YA}: M = 6.48; \text{OA}: M = 7.75)\).

Furthermore, there was a significant two-way interaction effect between postural load and listening load \((F(1.52, 42.52) = 13.73, p < .001)\). Two, one-way ANOVAs were conducted to consider firm standing conditions independently of compliant standing conditions. The post-hoc tests indicated that when standing on either a firm or compliant surface, COP path length was longer during high load \((\text{firm}: M = 8.26; \text{compliant}: M = 21.68)\) listening conditions than during no load \((\text{firm}: M = 6.46; \text{compliant}: M = 16.44)\) listening conditions \((p < .001\), compliant \(\text{OA} = p < .01)\). However, only during firm standing conditions was COP path length longer during high load \((M = 8.26)\) compared to low load \((M = 6.49)\) listening conditions \((p < .001)\). There were no observed differences in COP path length between high load \((M = 21.68)\) and low load \((M = 17.44)\) listening conditions during standing on a compliant surface.

There was also a significant two-way interaction effect between postural load and visual load \((F(1, 28) = 112.41, p < .001)\). The post-hoc tests indicated that although COP path length was longer during eyes closed compared to eyes open conditions for both firm \((p < .01)\) and compliant \((p < .001)\) standing conditions, the magnitude of the difference was greater during standing on a compliant surface \((\text{open}: M = 13.67; \text{closed}: M = 23.37)\) than during standing on a firm surface \((\text{open}: M = 6.47; \text{closed}: M = 7.68)\).

Lastly, there was a significant three-way interaction effect between group, visual load, and postural load \((F(1, 28) = 15.72, p < .001)\). A 2 (group) x 2 (visual load) ANOVA was conducted for both firm and compliant standing conditions. The ANOVAs indicated that during standing on a firm surface, COP path length varied as a function of visual load \((F(1, 28) = 28.16, p < .001)\) but not group, while during standing on a compliant surface, COP path length varied as a function of both visual load \((F(1, 28) = 144.93, p < .001)\) and group \((F(1, 28) = 55.42, p < .001)\). Further, a significant two-way interaction effect between group and visual load \((F(1, 28) = 17.34, p < .001)\) was seen within compliant standing conditions but not within firm standing conditions. In considering this interaction effect, the post-hoc tests indicated that when standing on a compliant surface the OA group exhibited longer COP path lengths than
the YA group during both eyes open \((p < .001)\) and eyes closed \((p < .001)\) conditions (see Figure 5).

![COP Path Length](chart)

**Figure 5.** Mean COP path length (cm) of younger versus older adults across the four visual and postural conditions collapsed across listening load. Error bars represent \(\pm SE\).

### 3.1.2 Older adults versus older adults with SCD

A 2 (group; OA vs. SCD) x 2 (postural load; standing firm vs. compliant) x 2 (visual load; eyes open vs. closed) x 3 (listening load; no load vs. low load vs. high load) mixed-factorial ANOVA was conducted on the COP path length measurements.

The ANOVA showed significant main effects of postural load \((F(1, 28) = 264.99, p < .001)\) and visual load \((F(1, 28) = 98.49, p < .001)\) with longer COP path lengths during standing on a compliant surface compared to a firm surface and with eyes closed compared to eyes open. There was also a significant main effect of listening load \((F(2, 56) = 63.27, p < .001)\) for which the post-hoc tests indicated that COP path length was longer during high load listening conditions compared to both low load \((p < .01)\) and no load \((p < .001)\) listening conditions. However, there was no observed difference between low load and no load conditions. Lastly, the main effect of group was not significant, therefore COP path length did not significantly differ between the OA and SCD groups \((p > .05)\).
The ANOVA showed a significant two-way interaction effect between group and postural load \((F(1, 28) = 6.23, p < .05)\). The post-hoc tests indicated that, when standing on a compliant surface, the OA group exhibited longer COP path lengths than the SCD group (OA: \(M = 25.15\); SCD: \(M = 20.32\); \(p < .01\)). However, the same was not true during firm surface standing conditions (\(p > .05\)) as the OA and SCD groups exhibited comparable COP path lengths (OA: \(M = 7.75\); SCD: \(M = 7.54\)). There was also a significant two-way interaction effect between group and visual load \((F(1, 28) = 5.25, p < .05)\). The post-hoc tests indicated that while the OA and SCD groups displayed comparable COP path lengths to each other during both eyes open (\(p > .05\)) and eyes closed (\(p > .05\)) conditions, both groups exhibited longer COP path length when performing eyes closed conditions compared to when performing eyes open conditions (\(p < .001\) for both comparisons). The magnitude of this difference between eyes open and eyes closed conditions was greater for the OA group (open: \(M = 12.75\); closed: \(M = 20.14\)) than for the SCD group (open: \(M = 11.62\); closed: \(M = 16.24\)).

Furthermore, there was a significant two-way interaction effect between postural load and listening load \((F(1.42, 39.86) = 18.85, p < .001)\). Two one-way ANOVAs were conducted to consider firm standing conditions independently of compliant standing conditions. The post-hoc tests indicated that when standing on either a firm or compliant surface, COP path length was longer during high load listening conditions than during both low load (firm = \(p < .001\), compliant = \(p < .01\)) and no load (firm = \(p < .001\), compliant = \(p < .001\)) listening conditions. However, the magnitudes of these differences were smaller during compliant standing conditions (no load: \(M = 19.46\); low load: \(M = 21.00\); high load: \(M = 27.27\)) compared to firm standing conditions (no load: \(M = 6.49\); low load: \(M = 6.92\); high load: \(M = 9.50\)).

There was also a significant two-way interaction effect between postural load and visual load \((F(1, 28) = 80.10, p < .001)\). The post-hoc tests indicated that although COP path length was longer during eyes closed compared to eyes open conditions for both firm (\(p < .01\)) and compliant (\(p < .001\)) standing conditions, the magnitude of the difference was greater during standing on a compliant surface (open: \(M = 17.25\); closed: \(M = 27.89\)) than during standing on a firm surface (open: \(M = 7.05\); closed: \(M = 8.23\)).

Lastly, there was a significant three-way interaction effect between group, visual load, and postural load \((F(1, 28) = 4.82, p < .05)\). A 2 (group) x 2 (visual load) ANOVA was conducted
for both firm and compliant standing conditions. The ANOVAs indicated that during standing on a firm surface, COP path length varied as a function of visual load ($F(1, 28) = 20.98, p < .001$), but not group. However, during standing on a compliant surface, COP path length varied as a function of both visual load ($F(1, 28) = 94.23, p < .001$) and group ($F(1, 28) = 4.67, p < .05$). Further, a significant interaction effect between group and visual load ($F(1, 28) = 5.30, p < .05$) was observed within compliant standing conditions but not during firm standing conditions. In considering this interaction effect, the post-hoc tests indicated that when standing on a compliant surface the OA group exhibited longer COP path lengths than the SCD group during eyes closed ($p < .001$) conditions. However, the same was not true during eyes open ($p > .05$) conditions (see Figure 6).

![COP Path Length](chart.png)

*Figure 6. Mean COP path length (cm) of older adults versus older adults with SCD across the four visual and postural conditions collapsed across listening load. Error bars represent ± SE.*

### 3.2 Listening task performance

Listening task performance was quantified and analyzed using the metric ‘response accuracy’. Response accuracy was calculated by obtaining the percentage of correctly identified digits per condition. Given that each condition consisted of six listening task trials, response accuracy was expressed as a percentage of the total number of auditory stimuli presented over six trials (i.e., 12 digits for low load conditions and 24 digits for high load conditions). For both low and high load
listening conditions, higher response accuracy equated to greater performance on the listening task.

As with postural control, the omnibus mixed-factorial ANOVA for listening accuracy also showed a significant main effect of group ($F(2, 43) = 3.98, p < .05$). Therefore, two separate analyses were conducted in alignment with the study hypotheses (one comparing the YA and OA groups, and a separate one comparing the OA and SCD groups); 2 (group) x 2 (visual load; eyes open vs. closed) x 2 (listening load; low load vs. high load) x 3 (postural load; sitting vs. standing firm vs. standing compliant) mixed-factorial ANOVAs were used. Significant main and interaction effects were subsequently subjected to post-hoc analyses consisting of multiple comparisons using the Bonferroni correction.

### 3.2.1 Younger versus older adults

The ANOVA showed a significant main effect of group ($F(1, 28) = 8.53, p < .01$) with the OA group exhibiting poorer response accuracy than the YA group. There was also a significant main effect of listening load ($F(1, 28) = 9.61, p < .01$) in which response accuracy was greater during low load listening conditions compared to high load conditions. There was a significant main effect of postural load ($F(2, 56) = 9.47, p < .001$) for which the post-hoc tests indicated that response accuracy was poorer during standing on a compliant surface compared to standing on a firm surface ($p < .05$). However, response accuracy during seated conditions was not seen to significantly differ from that during compliant or firm standing conditions ($p > .05$ for both comparisons). Lastly, the main effect of visual load was not significant, therefore response accuracy during eyes open and eyes closed conditions did not significantly differ ($p > .05$).

The ANOVA also showed a significant two-way interaction effect between group and listening load ($F(1, 28) = 4.27, p < .05$). The post-hoc tests indicated that the OA group had poorer response accuracy than the YA group during high load listening conditions ($p < .001$), but the same was not true during low load listening conditions ($p > .05$). Further, the OA group was seen to exhibit poorer response accuracy during high load listening conditions compared to low load conditions ($p < .001$), while the YA group exhibited comparable response accuracy between the two listening conditions (see Figure 7).
Additionally, there was a significant two-way interaction effect between postural load and visual load ($F(2, 56) = 5.27, p < .01$) for which two, one-way ANOVAs were conducted to consider eyes open conditions independently of eyes closed conditions. The post-hoc tests indicated that during eyes open conditions, response accuracy was poorer when standing on a compliant surface compared to when sitting (compliant: $M = 97.15$; sitting: $M = 98.89$; $p < .05$). However, there were no observed differences in response accuracy between postural load (sitting: $M = 97.71$; firm: $M = 99.03$; compliant: $M = 97.43$) during eyes closed conditions ($p > .05$ for all comparisons).

### 3.2.2 Older adults versus older adults with SCD

The ANOVA for listening accuracy showed a significant main effect of listening load ($F(1, 28) = 14.36, p < .001$) with higher response accuracy during low load listening conditions than during high load listening conditions ($p < .001$). However, the main effects of visual load, postural load, and group were not significant. Response accuracy did not significantly differ between the OA and SCD groups ($p > .05$), nor did it significantly differ
during eyes open and eyes closed conditions ($p > .05$) or during sitting, firm standing, and compliant standing conditions ($p > .05$).

The ANOVA also showed a significant two-way interaction effect between visual load and postural load ($F(1.56, 43.67) = 7.07 p < .01$). Two, one-way ANOVAs were conducted to consider eyes open conditions independently of eyes closed conditions; however, the post-hoc tests did not result in any comparisons that were significant ($p > .05$ for all comparisons).

### 3.3 Correlations with assessment session data

Additional exploratory analyses were conducted to consider how performance during the experimental session compared to performance during the assessment session where participants completed the baseline measures of sensory, motor, and cognitive functioning. Specifically, correlation matrices were used to quantify associations between baseline measures of sensory, motor, and cognitive functioning and experimental listening task and postural task performance. Only data from older adult participants (OA and SCD) was included, as younger adult participants did not complete the entire assessment session. Pearson’s correlation coefficient ($r$) was calculated for each comparison within the matrices. Statistical significance was then determined using a significance level of $p < 0.5$; however, as multiple correlations were performed without adjustment, the type 1 error rate was likely inflated.

#### 3.3.1 Postural control

A correlation matrix was conducted to quantify any associations between baseline measures and experimental session postural performance. Mean COP path length from each experimental session condition was correlated with the baseline measures obtained during the assessment session (see Figure 8).
In this matrix, measures of COP path length during particular experimental conditions were strongly negatively correlated with the MoCA, the WAIS-III Digit-Symbol Coding test, and the RAVLT immediate and delayed recall, while other experimental conditions were strongly positively correlated with the DTT and the TMT Trail B. According to Cohen’s (1988) guidelines, these specified correlations were all large in magnitude (i.e., $r \geq 0.5$). Note that higher scores on all baseline tests, aside from the DTT, the TUG, the Stroop test, and the TMT Trail A and Trail B, are associated with greater performance.

**3.3.2 Listening task performance**

A correlation matrix was conducted to quantify any associations between baseline measures and experimental session listening task performance. Mean response accuracy from each experimental session condition was correlated with the baseline measures obtained during the assessment session (see Figure 9).
Figure 9. Heat map illustrating correlations between OA and SCD participants’ baseline assessment performance and experimental listening task performance (response accuracy). Pearson’s correlation coefficient (r) represented in red tones (= negative) and blue tones (= positive). Note: * p < .05; EO = eyes open; EC = eyes closed

In this matrix, measures of response accuracy across several experimental session conditions were strongly negatively correlated with the DTT and strongly positively correlated with the MoCA and the DDT. Additionally, certain measures of response accuracy were strongly negatively correlated with the TUG, the Stroop test difference score, and the TMT Trail B. As in the matrix comparing baseline measures and experimental session postural performance, these specified correlations were generally large in magnitude according to Cohen’s (1988) guidelines. Note that higher scores on all baseline tests, aside from the DTT, the TUG, the Stroop test, and the TMT Trail A and Trail B, are associated with greater performance.
4 Discussion

There is a significant body of evidence suggesting that older adults experience larger dual-task costs than younger adults when performing a postural task with a concurrent cognitive task. Specifically, when dual-task paradigms are made to be sufficiently challenging, postural task performance (Doumas et al., 2008; Redfern et al., 2001), cognitive task performance (Rapp, Krampe, & Baltes, 2006), or both (Doumas et al., 2008; Shumway-Cook & Woollacott, 2000) are more greatly affected among older adults compared to younger adults. However, the extent to which these dual-task costs are experienced within everyday life is largely unknown as past paradigms have not accurately reflected typical challenges encountered in real-world situations. Therefore, this was explicitly addressed within the current study wherein a common everyday task, specifically listening in a multi-talker environment while maintaining standing balance, was considered.

There is evidence to suggest that older adults have more difficulty understanding speech than younger adults, particularly when multiple talkers are present (Martin & Jerger, 2005). Further, hearing difficulties have been demonstrated to be associated with mobility-related problems among the elderly (Agmon et al., 2017). In everyday life, older adults typically contend with these hearing- and mobility-related challenges while immersed in visually complex environments which can further challenge and/or benefit performance. For instance, complex visual surrounds may negatively affect listening performance by means of interference and/or distraction, while complex yet realistic visual environments may better support posture due to their enhanced cues to orientation. Thus, in order to examine the extent to which older adults’ postural and listening performance is affected by dual-task costs under more realistic, everyday conditions, I developed a postural dual-task paradigm wherein a spatial auditory processing task (i.e., the DDT presented over loudspeakers) was introduced as the cognitive task and virtual reality technologies were used to simulate a real-world environment. Using this paradigm, I looked to investigate the effects of aging and subjective cognitive declines on postural and listening performance under varying levels of sensory, motor, and cognitive challenge. Postural performance was assessed using measures of COP path length, while listening task performance was assessed using response accuracy. I hypothesized that 1) older adults (i.e., the OA group) would exhibit greater decrements in postural and listening task performance than younger adults (i.e., the YA group), and 2) older adults with SCD (i.e., the SCD group) would exhibit greater decrements in postural
and listening task performance than older adults without SCD (i.e., the OA group). Moreover, I predicted that these group differences would become larger under more challenging conditions, as listening load, visual load, and postural load increased.

Results demonstrated that, generally, age-related differences that aligned with the initial hypotheses were observed in postural performance when postural load was greatest (i.e., compliant surface) and in listening performance when listening load was greatest (i.e., high load listening). Removal of visual surrounds magnified these postural performance differences between YA and OA participants, while visual information had no added effect on listening performance differences. Furthermore, differential effects of managing increased listening load were observed among YA and OA participants that were reflective of postural prioritization by OA participants, such that listening performance decreased while stable posture was maintained. When performing the same dual-task under the same challenging conditions, OA and SCD participants exhibited comparable performance across conditions, with postural differences observed only during the most challenging postural conditions (i.e., eyes closed, compliant surface). The postural differences observed between OA and SCD participants were opposite in direction to the hypothesized differences in that OA participants exhibited poorer postural control than SCD participants. Therefore, in contrast to performance differences on certain baseline measures (i.e., OA participants performed better than SCD participants on the MoCA and the RAVLT immediate and delayed recall), no objective differences were observed between OA and SCD participants during the experimental session that were suggestive of SCD participants experiencing greater difficulties than their age-matched peers without SCD.

In the following sections I will describe the above-mentioned experimental findings in greater detail while considering how they align with my study hypotheses and the current literature. I will then consider how certain experimental findings relate to participants’ baseline assessment measures and provide interpretations of observed associations. Lastly, I will discuss the limitations of the current study and propose directions for future research.

4.1 Effect of aging

In order to examine the effect of aging, I considered both postural performance and listening task performance of YA and OA participants. When examining postural performance, OA participants were observed to have longer overall COP path lengths than YA participants. This
observation suggests that the OA group had poorer postural control across conditions, which aligns well with the body of work indicating that postural control is vulnerable to the effects of aging (Bugnariu & Fung, 2007; Maki & McIlroy, 1996; Maylor & Wing, 1996). Further, in support of my initial hypothesis, COP path length was observed to vary as a function of visual load, postural load, and listening load. Specifically, COP path length became longer as load was incrementally increased (i.e., eyes open to closed; firm to compliant surface; no/low to high load listening). As increases in COP path length are thought to be indicative of declines in one’s ability to maintain a stable posture, this suggests that postural control was negatively affected by increases in visual, somatosensory/motor, and listening/cognitive challenge. These findings generally align with existing research on cognitive and sensory contributions to postural control indicating that one’s ability to maintain postural stability is challenged when sensory information is disrupted or excluded and/or when cognitive load is increased (Boisgontier et al., 2013; Teasdale et al, 1991; Woollacott & Shumway-Cook, 2002).

Previous studies that have considered upright standing balance with concurrent cognitive tasks have demonstrated that older adults typically experience greater decrements in postural performance than younger adults under dual-task conditions. However, this trend often only becomes significant when the difficulty of the postural task is sufficiently increased (Doumas et al., 2008; Rapp et al., 2006; Redfern et al., 2001; Shumway-Cook & Woollacott, 2000). In the current study, OA participants were seen to exhibit significantly less stable posture than YA participants when postural load was increased to compliant surface standing. Notably, the magnitude of this age-related difference was greatest during eyes closed conditions, suggesting that, although increasing the somatosensory challenge provided sufficient sensitivity to reveal age-related effects, increasing the visual and somatosensory challenge provided even greater sensitivity. These findings support my hypothesis in that age-related differences in postural performance were greatest under the most challenging conditions. Moreover, they align with previous reports of age-related changes in postural control wherein visual and somatosensory challenge was increased (Doumas et al., 2008; Redfern et al., 2001; Shumway-Cook & Woollacott, 2000; Teasdale et al., 1991).

When examining listening task performance, there was also evidence of an age-related difference in listening response accuracy. Specifically, OA participants were seen to exhibit poorer overall listening response accuracy than YA participants. In alignment with previous findings of an
inverse relationship between age and DDT performance (Mukari, Umat, & Othman, 2010; Strouse, Wilson, & Brush, 2000; Wilson & Jaffe, 1996), this observed group difference supports my initial hypothesis that the OA group would have greater overall decrements in listening performance than the YA group. Further, when considered with respect to listening load, the group difference in listening task performance suggests that OA participants had poorer response accuracy than YA participants in high load listening conditions. However, during low load listening conditions, there was no observed difference between the YA and OA groups, suggesting that the low load listening task was not sufficiently challenging to expose any age-related differences in response accuracy. The strength of the inverse relationship between age and DDT performance has been reported to be dependent on task complexity (Strouse et al., 2000; Wilson & Jaffe, 1996). For instance, Wilson and Jaffe (1996) demonstrated that, when tasked with dichotic digit listening, older adults exhibit poorer overall recognition performance than younger adults. Moreover, they demonstrated that increasing listening task complexity by going from 1-pair to 2-pairs to 3-pairs to 4-pairs of dichotic digits results in a systematic decrease of recognition performance, particularly among older adults. Therefore, as OA participants exhibited poorer overall response accuracy and were more greatly affected by increases in listening load, YA and OA participants’ observed patterns of listening task performance can be said to complement these reports of more complex tasks displaying greater age-related differences in listening performance.

Interestingly, despite OA participants’ poorer overall postural control, increases in listening load were observed to have greater effects on YA participants’ postural performance than on that of OA participants. The fact that the OA group was able to maintain more consistent posture across listening loads suggests that OA participants may have preferentially prioritized their posture over the listening task. Termed the “posture first” response, this pattern of prioritization is commonly observed among older adults in the context of cognitive-motor dual-tasks due to their tendency to prioritize their physical safety over cognitive performance (Li, Krampe, & Bondar, 2005). Previous studies have demonstrated that older adults’ adoption of this particular strategy is dependent on the degree of postural threat experienced (Shumway-Cook, Woollacott, Kerns, & Baldwin, 1997). Therefore, only when postural task demands and/or cognitive load are sufficiently increased do older adults tend to prioritize their posture by investing cognitive resources into the maintenance of postural stability over other tasks. This was demonstrated in
the current study wherein OA participants appeared to preferentially allocate cognitive resources to postural control as listening load was increased. Further, in considering listening response accuracy with respect to listening load, the group difference in listening task performance provides additional evidence of OA participants’ adoption of the “posture first” response, in that there appears to have been a trade-off between OA participants’ postural performance and listening performance under high load listening conditions (i.e., posture was unaffected, but listening performance decreased under high listening load conditions). Evidenced by the interaction between listening load and age, response accuracy of OA participants declined as listening load increased from low to high while response accuracy of YA participants remained consistent between listening loads. The fact that YA participants did not exhibit a similar decline in listening performance suggests that they were not affected by increases in cognitive challenge and were therefore able to successfully perform both low and high load listening conditions despite having to simultaneously maintain standing balance. Given that few studies have considered auditory processing specifically while systematically controlling for peripheral hearing loss within the context of postural dual-tasks, these findings provide unique insight into how younger and older adults differentially manage the maintenance of postural stability when tasked with a common everyday experience – effortful listening.

Furthermore, when considering listening task performance with respect to postural load, response accuracy of YA and OA participants was observed to be poorer during compliant standing conditions compared to firm standing conditions. This decline in response accuracy was further supported by the interaction between postural load and visual load, in which YA and OA participants’ response accuracy was seen to decline as postural load increased during eyes open conditions only (see Appendix A). As demonstrated by Lajoie et al. (1993), the cognitive demands of postural control increase in parallel with the demands of a postural task. Therefore, under more challenging postural conditions, such as standing on a compliant surface, fewer cognitive resources are available to be allocated to a secondary task. There is also evidence to suggest that visual information that is not relevant to the task at hand can further detract from the cognitive resources available for allocation (Guerreiro, Murphy, & Van Gerven, 2010). As such, under eyes open, compliant standing conditions, cognitive resources were likely in high demand which in turn appeared to negatively affect listening task performance. These findings are particularly interesting given that virtual reality technologies were used in this study, not only to
create a more realistic visual environment, but also to reflect the complexities of the real-world and account for the potential distractibility of typical everyday visual surrounds. While visual distraction has been shown to negatively affect auditory-visual speech perception (Cohen & Gordon-Salant, 2017), little is known about the effects of realistic visuals on auditory-only speech perception, particularly under dual-task conditions. Therefore, these findings extend current knowledge by demonstrating that, when postural load is increased (i.e., compliant standing conditions), typical visual information encountered in everyday environments can have a significant effect on listening performance. Specifically, they suggest that one’s ability to understand speech in noise declines when tasked with a challenging postural task in a visually complex environment. However, in the current study, no age-difference was observed with respect to the effects of postural load and visual load on response accuracy. Therefore, while these findings provide novel insight into the interactions between postural load and visual load as they relate to listening performance, they do not suggest that the degree of these interaction effects differs between younger and older adults under the conditions included here.

4.2 Effect of subjective cognitive decline

In examining the effect of subjective cognitive ability, I considered OA and SCD participants’ postural performance and listening task performance across conditions. When examining postural performance of both groups (OA and SCD), posture was observed to become less stable as visual load, postural load, and listening load was increased. Therefore, postural control of SCD participants was similarly affected by increases in visual, somatosensory/motor, and listening/cognitive challenge to that of OA and YA participants. However, contrary to my initial hypothesis, the SCD group did not exhibit poorer overall postural performance than the OA group. Instead, OA and SCD participants were observed to exhibit comparable postural stability during firm standing conditions, and interestingly, SCD participants exhibited greater postural stability than OA participants during compliant standing conditions. When considered with respect to visual load, the group difference in postural performance was only observed during eyes closed, compliant surface conditions. Therefore, only when the visual and somatosensory challenge was greatest, did the postural task elicit significant group differences between OA and SCD participants. This mirrors the aging literature in that concurrent visual and somatosensory manipulations typically result in greater sensitivity to group differences during postural dual-task conditions (Doumas et al., 2008; Redfern et al., 2001; Shumway-Cook & Woollacott, 2000).
However, OA and SCD participants’ comparable postural performance across most conditions, and SCD participants’ superior postural performance during the most challenging conditions was unexpected. That said, the fact that these findings do not align with my initial hypothesis should not undermine their contributions to a limited but important literature.

In investigating the physical functioning of individuals in the early stages of the cognitive continuum, few studies have considered individuals with SCD specifically (Shin et al., 2015). Although there is some recent evidence of an association between SCD and an increased risk of falls (Al-Sari, Tobias, Archer, & Clark, 2017), little is known about how this is reflected in measures of postural control, particularly under challenging conditions. As such, my hypothesis was largely based on evidence suggesting that sensory and motor changes may be some of the first exhibited symptoms of dementia during the prodromal phases, even before cognitive symptoms emerge and before a formal diagnosis is made (Albers et al., 2015). Further, balance and mobility impairments are also common early symptoms among individuals with MCI and AD (Bahureksa et al., 2017; Shin et al., 2011; Szczepańska-Gieracha, Cieślik, Chamela-Bilińska, & Kuczyński, 2016). Therefore, my hypothesis that individuals with SCD would exhibit greater problems with postural control than those without SCD was rooted in the assumption that individuals’ subjective concerns of declines were indicative of early atypical cognitive decline. Moreover, it assumed that the paradigm used in this study was sensitive to differences between individuals with and without these early cognitive declines. However, as discussed in detail below, it is possible that not all SCD participants’ perceived declines were actually telling of true impairments, or perhaps they were but the study paradigm was not sensitive to them.

If SCD participants’ perceived declines were not indicative of true impairments, it is likely that their subjective concerns were driven by others factors, and therefore their performance on the experimental task would not be expected to differ from that of OA participants. For instance, there are many potential reasons for which one may present with SCD – psychiatric conditions, personality traits, neurological and medical disorders, and substance use (Jessen et al., 2014; Reisberg et al., 2008). Notably, several studies have suggested an association between cognitive complaints and depression, anxiety, and certain personality traits (Buckley et al., 2013; Comijs, Deeg, Dik, Twisk, & Jonker, 2002; Hohman, Beason-Held, & Resnick, 2011; Slavin et al., 2010; Stogmann et al., 2016). As such, although SCD participants in this study did not report any symptoms of depression or anxiety when explicitly asked, their experience with SCD may have
been influenced by factors outside of non-normative cognitive decline. Therefore, their observed postural performance may not have accurately reflected early changes in cognition per se. Moreover, certain individuals, particularly those who have a family history of dementia and/or are overly concerned about their health, may express subjective concerns about their cognition that do not stem from actual declines but rather from a heightened sense of worry (i.e., the “worried well”). Thus, it is possible, given the above-mentioned factors, that some SCD participants were not in fact in the earliest stages of cognitive decline, hence their observed postural performance that was comparable to that of OA participants.

Alternatively, the subjective concerns of individuals with SCD may be telling of true declines but the current study may not have successfully captured these individuals’ experiences of impairment. In this regard, this study may have been limited by a sampling bias wherein a disproportionate number of individuals with unwarranted SCD were recruited. It has been suggested that recruitment setting (i.e., community versus clinical) bears influence on SCD’s associated risk of progression to dementia (Mendonça, Alves, & Bugalho, 2016; Perrotin et al., 2017). For instance, individuals presenting to memory clinics with cognitive complaints are more likely to be experiencing true non-normative age-related changes given that their perceived impairments are often more serious in nature (Rabin et al., 2017). In contrast, community-based samples typically consist of a higher proportion of “worried well” since the number of people presenting with complaints in non-clinical settings far exceeds that which would be found in a clinical setting (Mitchell, Beaumont, Ferguson, Yadegarfar, & Stubbs, 2014). Considering a random community-based sample was used in the current study, it is reasonable to think that a relatively large portion of the SCD group was made up of the “worried well”. This in turn may have limited the study’s representation of impairment experienced by individuals with warranted SCD. Further, it is also possible that this study’s dual-task paradigm may not have been best suited to capture group-related differences between individuals with and without SCD. For instance, perhaps the experimental task (i.e., listening while standing under challenging conditions) did not sufficiently tax the cognitive abilities that individuals with SCD are most troubled by (e.g., memory).

That said, OA and SCD participants were found to differ with respect to their postural performance during eyes closed, compliant surface conditions (i.e., the most challenging postural conditions), but in the opposite direction than originally hypothesized. One possible explanation
for this observed group-related difference is that SCD participants did not have true cognitive impairments but overcompensated because of their subjective concerns. In other words, if SCD participants were unjustifiably worried about their cognition they may have tried harder in order to compensate for their perceived declines, in turn performing better than individuals without their same worries (i.e., SCD participants may have been more motivated and therefore expended greater amounts of effort than OA participants). An alternative explanation is that SCD participants did have true declines and had to adapt accordingly, making them more hypervigilant than OA participants. This hypervigilance could have in turn been what caused the SCD group to exhibit greater postural stability than the OA group. Although it is not clear whether or not the subjective concerns of SCD participants were telling of true impairments, this observed difference in OA and SCD participants’ postural performance during the most challenging conditions certainly warrants further exploration.

In examining overall listening task performance, response accuracy was observed to vary as a function of listening load only, with OA and SCD participants exhibiting declines in response accuracy as listening load increased from low to high. This observed decline in response accuracy suggests that the manipulation of listening load was effective in that it modulated listening performance in the expected direction. However, there was no observed group difference in listening task performance as was originally hypothesized. The SCD group did not exhibit significantly poorer response accuracy than the OA group but rather both groups were observed to exhibit relatively comparable response accuracy across all conditions. Deficits in auditory processing have been suggested to be a significant predictor of cognitive decline (Gates et al., 1996; Gates et al., 2011). Specifically, performance on the DDT has been evidenced to be associated with cognitive difficulties in older adults that may manifest years in advance of dementia symptoms (Gates et al., 2008; Gates et al., 2011; Gates, Beiser, Rees, D'Agostino, & Wolf, 2002; Idrizbegovic et al., 2011). Therefore, individuals with SCD who are at risk of later being diagnosed with dementia would be expected to exhibit greater performance decrements on the DDT, particularly when performed under challenging conditions. However, no significant differences in OA and SCD participants’ listening task performance were observed in this study. That said, there was a general trend suggestive of SCD participants exhibiting poorer listening task performance than OA participants across most conditions (see Appendix B). This observed pattern of listening performance suggests that either auditory processing was only impaired
among some SCD participants, or perhaps the listening task, even when performed under the most challenging conditions, was not sufficiently sensitive to existing impairments. Moreover, the above-mentioned factors related to the etiologically heterogeneous nature of SCD could have contributed to the observed pattern of listening task performance among OA and SCD participants, such that individuals with SCD due to factors outside of atypical cognitive changes would not be expected to exhibit poorer listening performance than individuals without SCD. Taken together, the listening task used in the current study may not have been sufficiently sensitive and/or the SCD group may have been too variable to allow for the observed trend to become significant; hence SCD and OA participants’ statistically similar listening performance.

4.3 Associations between baseline and experimental measures

4.3.1 Comparing older adults with and without SCD

The OA and SCD groups performed comparably on all baseline assessments aside from the MoCA and the RAVLT immediate and delayed recall. On these particular assessments, the SCD group exhibited poorer performance than the OA group. This observed pattern of performance presents as an interesting and counterintuitive contrast whereby the only distinguishing group differences observed on baseline measures were in the opposite direction of the observed differences between OA and SCD participants during the experimental session (i.e., better postural performance among SCD participants compared to OA participants in the most challenging conditions). Although it is unclear why exactly this is case, I have considered two potential explanations for these opposing observations. The first relates to the fact that the MoCA and the RAVLT target highly specific cognitive processes, whereas the dual-task paradigm used in the experimental session targets more general cognitive processes while also simultaneously targeting sensory and motor processes. As such, if SCD participants had true, yet highly focused cognitive declines, tasks targeting specific cognitive abilities may have been better suited to expose these differences between OA and SCD participants in the experiment. That said, this proposed task-related difference does not explain why SCD participants were observed to have superior postural performance than OA participants during the experimental session. Therefore, I considered a second explanation relating to differences in how the assessments used in each session (i.e., assessment versus experimental) were framed. Specifically, measures such as the MoCA and the RAVLT are both easily identifiable as assessments of cognition; whereas, the dual-task paradigm used in the experimental session is
more similar to a real-world task and therefore its purpose in terms of assessment is likely less obvious. As such, for individuals troubled by their memory and/or thinking, such as those with SCD, the MoCA and the RAVLT may have elicited a self-fulfilling prophecy wherein performance suffered due to increased anxiety surrounding formal cognitive testing. Conversely, when asked to perform a task that was more reflective of everyday situations, these individuals may have been less discouraged by their perceived cognitive abilities and therefore better able to perform the task successfully; hence their observed superior postural performance. That said, this ‘framing issue’ would only be expected to hold so long that SCD participants belonged to the “worried well”, meaning they did not have true atypical declines in cognition. Further, it is possible that the study’s exclusion criteria, wherein individuals with below cutoff MoCA scores were excluded from the OA group but not from the SCD group, may have contributed to the observed group differences on the MoCA and RAVLT. Therefore, although interesting, these somewhat contradictory baseline versus experimental task findings should be interpreted cautiously without further investigation. That said, in collapsing across all older adult participants (OA and SCD) and categorizing according to an objective cognitive measure (i.e., the MoCA) rather than a subjective cognitive measure (i.e., SCD), it is made apparent that participants with below cutoff MoCA scores (< 26) generally exhibited poorer experimental postural and listening performance than participants with above cutoff scores (≥ 26) (see Appendix C). This suggests that an association between objective cognitive performance and experimental performance may well exist; however, it may not have been reflected in the OA versus SCD comparison given that, as previously proposed, not all SCD participants may have had true cognitive declines.

4.3.2 Collapsed across older adults with and without SCD

When looking across the spectrum of older adult participants (OA and SCD), rather than between groups, I examined how their performance on a complex task reflective of everyday challenges compared to standard measures of audition, mobility, and cognition. Specifically, I considered whether their baseline assessment performance was associated with their experimental performance; first considering associations with postural task performance and then considering associations with listening task performance.
4.3.2.1 Baseline measures versus postural control

In examining older adult participants’ postural performance and baseline measures, greater postural sway (i.e., less stable posture) during particular experimental conditions was found to be associated with poorer performance on measures of global cognitive functioning, processing speed, and verbal learning and memory. This was evidenced by the strong, negative correlations between COP path length and the MoCA, the WAIS-III Digit-Symbol Coding test, and the RAVLT immediate and delayed recall. Under other experimental conditions, COP path length was found to be positively correlated with the DTT and the TMT Trail B, suggesting that poorer performance on measures of speech recognition and executive function was associated with poorer postural control. These findings provide support for the age-related shift towards greater cognitive control of posture (Boisgontier et al., 2013), in that they depict an association between poorer postural performance and declines in certain cognitive abilities among this particular group of older adults. Furthermore, the observed association between the TMT Trail B and COP path length aligns with previous findings in which executive function, as measured by the TMT Trail B, was found to be independently associated with balance control (Tangen et al., 2014).

Interestingly, there were no observed associations between experimental postural performance and the DDT or the CRM. Of the three baseline assessments involving auditory processing (i.e., the DDT, the CRM, and the DTT), only the DTT was found to be associated with postural performance in that higher speech reception thresholds on the DTT were associated with less stable posture. This pattern of observations suggests that the ability to understand speech in noise was only limitedly associated with postural control. However, as there was little variation in participants’ performance on these baseline measures, it is unlikely that the observed association is telling of the true relationship between auditory processing and postural control. Specifically, performance on the DDT and CRM was near ceiling. Therefore, it is possible that the observed association was limited by the lack of sensitivity of these measures to differences among OA and SCD participants’ auditory processing abilities.

4.3.2.2 Baseline measures versus listening task performance

When examining older adult participants’ listening task performance (i.e., the DDT in StreetLab) and baseline measures, lower response accuracy across several experimental conditions was observed to be associated with poorer performance on measures of global cognitive functioning
and auditory processing (i.e., the MoCA, the DDT, and the DTT). Moreover, listening response accuracy under certain experimental conditions was positively associated with performance on the TUG, the TMT Trail B, and the Stroop test, such that poorer listening task performance was associated with poorer performance on measures of functional mobility, executive function, and cognitive interference. As in the comparison to postural performance, the observed associations between baseline measures and listening task performance demonstrate that older adults’ listening response accuracy was related to their objective cognitive abilities. This, in turn, suggests that their ability to understand speech in noise may be related to their cognitive reserve (i.e., availability of cognitive resources), and thus aligns with the documented relationship between speech understanding and cognition (CHABA, 1988). Furthermore, the strong, positive correlation between experimental listening task performance and baseline DDT performance provides reassurance that older adults’ performance on the DDT was consistent between testing environments (i.e., ideal listening conditions in a sound booth vs. realistic, real-world conditions in the virtual reality laboratory; see also Campos et al., under review). That said, it is interesting to note that while the DDT and DTT were both significantly associated with experimental listening performance, there was no observed association between performance on the experimental listening task and the CRM. This suggests that the processes targeted by the CRM may differ from those targeted by the DDT and DTT. Given that spoken phrases are used as the stimuli in the CRM, while spoken digits are used in the DDT and DTT, it is possible that this observed difference in associations stems from inherent differences between these particular task types.

Taken together, the observed associations between baseline measures and experimental performance (postural control and listening task performance) indicate a clear trend in the associations between objective measures of cognition and experimental performance among older adults.

4.4 Limitations and future directions

While the introduction of virtual reality technologies allowed for the complexities of real-world environments to be more accurately reflected, the visual manipulations used (eyes open versus closed) limited the extent to which conclusions could be made about the effects of complex visual information on postural and listening task performance. For instance, by having
participants open and close their eyes while immersed in a static simulation of downtown Toronto, the current study could only speak to the effects of adding/removing static visual information. Therefore, future research should include a dynamic simulation (i.e., introduce moving pedestrians and vehicles) in addition to the static simulation, in order to more explicitly examine the potential for visual interference and/or augmentation within the context of a dual-task paradigm involving listening while standing. Doing so could prove to increase the sensitivity of the experimental task to age-related differences, given that older adults are thought to be more vulnerable to cross-modal visual distraction than younger adults (Guerreiro et al., 2013).

When investigating the sensitivity of the dual-task paradigm to subjective cognitive ability, the study’s cross-sectional design presented as a limitation. Reliant on valid categorization of participants, this design made it difficult to ensure that observed group differences between OA and SCD participants were solely due to factors related to cognitive decline. As one’s risk of developing dementia can only be confirmed via longitudinal studies, ensuring that participants assigned to the SCD group were at increased risk of developing dementia was not possible. That said, the purpose of the study was not to determine SCD participants’ relative risk of future cognitive decline, but rather to determine whether any objective behavioral differences existed between older adults with and without subjective cognitive complaints when tasked with a challenging yet realistic everyday situation.

In a similar vein, the construct of SCD, in and of itself, proved to be a limitation within the current study, and is in fact a widespread challenge throughout this literature. As SCD has multiple underlying etiologies, it is possible that expressions of SCD carry different meanings despite presenting to be similar in nature (Rabin et al., 2017). As such, classifying participants according to their subjective cognitive ability – a measure that is based on self-report – may have resulted in participants being assigned to the SCD group despite not having true cognitive declines or being at increased risk of developing dementia. For instance, a sub-set of the SCD group may have had genuine cause for concern, whereas another sub-set may have belonged to the “worried well”. This heterogeneity within the SCD group could have in turn diminished between-group differences; particularly as the sample size was relatively small. That said, further exploration of these proposed ‘sub-categories’ of SCD, and discovery of tools that can better differentiate between them, could allow for more accurate categorization of individuals with
SCD and in turn help extend current literature on SCD’s associated risk of future cognitive decline.

Moreover, with evidence to suggest that SCD is strengthened as a measure of preclinical AD when paired with assessment of AD biomarkers (Rabin et al., 2017), future research should consider biomarker status alongside SCD in order to assess whether individuals who have objective evidence of being in the preclinical stages of AD exhibit performance decrements on everyday mobility-related tasks. Further, inclusion of participants with MCI and/or AD could also be of value in providing additional points of comparison along the spectrum of cognitive decline. In this respect, I made a concerted effort during my thesis to recruit individuals with MCI and AD; however, recruitment of these individuals proved to be a significant challenge.

Generally, I recruited high functioning older adults while trying to control for common age-related conditions (i.e., sensory loss, mobility impairments, and other general health conditions). Although this was intentional in order to expose specific effects of SCD, it may have led to a biased sample and/or did not allow for other interactions that could be naturally co-occurring. For instance, there is some evidence to suggest that hearing loss is associated with cognitive decline (Lin et al., 2011). Therefore, excluding individuals with hearing loss may have resulted in a specific group of older adults with SCD that was not necessarily reflective of the general population. As such, future research should consider a wider range of individuals, specifically individuals with peripheral and/or central hearing loss and/or existing mobility-related problems. Consideration of such individuals within the context of this study’s dual-task paradigm could further extend current knowledge regarding the association between hearing, cognition, and balance.

5 Conclusions

The goal of this study was to determine the effect of age and subjective cognitive ability on the performance of a complex, everyday task involving standing while listening in a real-world setting. Taken together, these findings provide support for the documented decline in postural control and auditory processing with aging, while demonstrating that older adults tend to prioritize their posture when tasked with standing while listening in a multi-talker, visually complex environment. Moreover, they suggest that either the dual-task paradigm used in this
study was not sensitive to early non-normative changes in cognition, or that the individuals in the SCD sample included here did not exhibit true declines in cognition.
References


Figure A.1. Mean listening response accuracy (%) in eyes open versus eyes closed conditions across the three postural load conditions collapsed across group (YA and OA) and listening load. Error bars represent ± SE.
Appendix B

**Figure B.1.** Mean listening response accuracy (%) of older adults versus older adults with SCD between the two listening load conditions collapsed across postural load and visual load. Error bars represent ± SE.

**Figure B.2.** Mean listening response accuracy (%) of older adults versus older adults with SCD across the six visual and postural conditions across listening load. Error bars represent ± SE.
Appendix C

**Figure C.1.** Mean COP path length (cm) of older adults with and without SCD across all conditions overlaid with individual data points labeled according to MoCA score where EO = eyes open and EC = eyes closed.

**Figure C.2.** Mean listening response accuracy (%) of older adults with and without SCD across all conditions overlaid with individual data points labeled according to MoCA score where EO = eyes open and EC = eyes closed.