The Impact of Multisensory and Cognitive Load on Younger and Older Adults' Cognitive-Motor Dual-Task Performance

Berkley Petersen

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By: Berkley Petersen

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Signed by the final examining committee:

Dr. Kristen Dunfield Chair

Dr. Aaron Johnson Examiner

Dr. Emily Coffey Examiner

Dr. Karen Li Thesis Supervisor

Approved by ______________________________
Dr. Aaron Johnson
Chair of Department or Graduate Program Director

____
Dr. Pascale Sicotte
Dean of Faculty

Abstract

The Impact of Multisensory and Cognitive Load on Older Adults' Cognitive-Motor Dual-Task Performance

Berkley Petersen

Maintaining postural control efficiently is dependent upon the coordination of motor, sensory and cognitive systems, all of which are subject to decline with aging. Evidence suggests that increased cognitive load, sensory loss and cognitive impairments alone reduce postural control, but rarely are these factors considered in conjunction. We therefore investigated how younger and older adults' postural control was impacted by increased cognitive load, simulated vision impairment, and hearing loss. Using a Nintendo Wii Balance Board, 32 younger (*M* = 23.03 S*D* = 3.53), and 27 older adults, 16 with hearing loss, (*M* = 77.13 *SD* = 7.53) and 11 without hearing loss (*M* = 71.27 *SD* = 11.30), underwent five balance conditions (i.e., eyes closed, normal and low vision single- and dual-tasks). We found that as task complexity increased (i.e., presence of a visual and/or backwards counting task), postural control decreased. Younger adults outperformed older adults on all tests of postural control, whereas minimal variations in postural performance existed between older adults with and without hearing loss. Older adults with hearing loss had greater medial-lateral sway in single-task normal and low vision conditions. Positive dual-task postural costs were evident among all three groups, but no group differences existed. Under normal and low vision conditions, older adults without hearing loss displayed positive dual-task cognitive costs, while those with hearing loss experienced no costs, suggesting differences in task prioritization. Taken together, our results illustrate that aging impacts how increased cognitive load and the presence of vision impairment challenge can affect postural control.

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The Impact of Multisensory and Cognitive Load on Younger and Older Adults' Cognitive-Motor Dual-Task Performance

Postural stability (i.e., balance) is a complex skill dependent upon the coordination of motor, sensory and cognitive systems which are subject to decline with healthy aging (Woollacott & Shumway-Cook, 2002). For example, Era et al. (2006) tested postural control among adults aged 30 years and older and found balance deterioration starts at a young age and further accelerates from 60 years of age onwards. Specifically, balance was worse among the 40- to 49-year-olds compared to the 30- to 39-year-olds. The decline due to aging is in many cases more pronounced in males compared to females. When studying factors contributing to postural instability, it is important to consider cognitive and sensory impairments as they are highly prevalent among older adults. Mild Cognitive Impairment (MCI) affects 15% - 20% of individuals 60 years and older (Petersen, 2016). Hearing loss affects approximately one-third of adults 61 to 70 years of age and more than 80% of adults older than 85 years (Walling & Dickson, 2012). Moreover, over 4 million Canadians between the ages of 45-85 years have at least mild vision loss (Mick et al., 2021). Both hearing and vision loss and MCI have shown to increase instability and falls risk (Doumas et al., 2008; Shaw et al., 2003). Nearly 20% - 30% of older adults fall each year, and falls remain the leading cause of injury-related hospitalizations among Canadian seniors (Statistics Canada, 2016). Further considering that between 2015 and 2050, the world population aged 60 and over is expected to reach 2 billion (World Health Organization, 2018) suggests that the prevalence rates will continue to rise. It is troublesome that as a function of age, the interactions between sensory functioning, cognition, and mobility continue to increase, meaning declines in one modality is likely to have consequences on other functions (Koh et al., 2015). Approximately 67% of seniors report experiencing two or more sensory deficits (Correia et al., 2016), yet research on the impact of multisensory impairments on balance and falls is limited compared to the effects of single sensory impairments. As such, there is a critical need to understand the interactions between multi-sensory impairments, cognitive decline, and motor functioning to preserve healthy aging and mobility.

The Role of Attention in Posture

Attention is needed for postural control (i.e., balance), for sensory integration, processing, and selecting motor responses to maintain or bring the body back to equilibrium (Redfern et al., 2001). Static balance can strain cognitive factors such as attention, especially when standing tasks becomes more challenging, or when a secondary cognitive task is implemented (Huxhold et al., 2006; Redfern et al., 2001). The dual-task paradigm, which consists of completing a motor and cognitive task alone and then simultaneously, is often used to examine the attentional demands needed to regulate the cognitive and motor tasks (Anderson et al., 2002; Woollacott, 2000). Given that cognitive, sensory and motor functions compete for limited attentional capacity, researchers have argued that older adults have fewer cognitive resources available for dividing attention between secondary tasks and maintaining static balance (Li et al., 2001; Woollacott & Shumway-Cook, 2002). Therefore, when two tasks are performed simultaneously, and require more than the total amount of available resources, dual-task costs occur, meaning performance on either or both tasks declines. It is often found that these costs are higher in older adults as they have limited cognitive resource capacity compared to younger adults (Anderson et al., 2002; Doumas et al., 2009; Woollacoot & Shumway-Cook, 2002). Taking such findings into consideration, it has been proposed that under dual-task conditions, the relationship between postural control and cognitive demand is U-shaped, meaning postural control improves when the cognitive demand is low and decreases when the cognitive demand is high (Lacour et al., 2008). Huxhold et al. (2006) suggested an easy secondary task (i.e., low cognitive demand) may benefit postural stability because it provides an external focus of attention, shifting attention away from the balance task. Conversely, a more difficult task with high demands has negative effects on posture due to attentional resource competition between cognitive and sensorimotor processes. During static balance tasks, participants are instructed to stand as still as possible usually with their arms at their sides, which can lead to an internal focus on postural control. It has been suggested that the direction of attention to the highly automatized process of balancing alone leads to reductions in postural control (Huxhold et al., 2006; Wulf et al., 2004). With the addition of a secondary task, postural benefits can be observed as it provides an external focus of attention (McNevin & Wulf, 2002). To illustrate, Stoffregen et al. (2000) asked participants to perform a quiet standing task while searching for letters in a block of text and then again while inspecting a blank piece of paper situated in front of them. They found that the visual search task reduced participants' postural sway compared to the inspection task, suggesting postural sway was reduced to facilitate visual search. It is important to note that they also observed reductions in postural sway when participants fixated on near targets as opposed to far targets. Kapoula and Lê (2006) similarly found that younger and older adults demonstrated a decrease in anterior-posterior and lateral body sway and variance of sway velocity when fixating on an object at 40 cm compared to 200 cm away.

However, discrepancies within the literature exist which question the effects of a secondary cognitive task on postural control. For example, some researchers have found that postural stability is compromised by the addition of cognitive load (Andersson et al., 1998, Maylor & Wing, 1996, Shumway-Cook & Wollacott, 2000; Shumway-Cook et al., 1997) while other have demonstrated postural benefits with the inclusion of a cognitive task (Andersson et al., 2002; Swan et al., 2004). Pellecchia (2003) found younger adults aged 18-30 years who completed a backwards 3s subtraction task, reversal task, and classification task showed increased center of pressure path length (i.e., postural instability). Similarly, Condron and Keith (2002) demonstrated the addition of a backwards 3s task increased instability on stable and titling platforms in younger (mean age = 26.4) and healthy older adults (mean age = 73.8). No age-related differences in stability were apparent under stable platform conditions. However, the inclusion of an older participant group with increased falls risk (mean age = 74.8) displayed significantly more sway than the young adults on all test conditions and more sway than the healthy older adults on the stable platform and forward backward tilting conditions (Condron & Keith, 2002). These results suggest the cognitive task interfered with the maintenance of stability due to resource competition, and such competition is more pronounced in older adults with a history of falling.

Other empirical evidence has established that performing a concurrent cognitive task while standing enhances postural control in younger adults (Riley et al., 2003; Riley et al., 2005). When examining this paradigm in older adults Jamet et al. (2004) found that among older adults aged 60 and over, a visuo-verbal Stroop task did not provoke higher instability during static balance, whereas a mental counting task did. A positive correlation between the degree of visual dependency and postural perturbation suggests the execution of a mental counting task causes changes in visual attention from external landmarks (i.e., looking at a colored word), to internal visual images (i.e., mental math). Given that older adults are more dependent than younger adults on visual information during postural regulation, losing external visual stimuli when executing a cognitive task explains reduction in postural performance. Melzer et al. (2001) found older adults exhibited less postural sway than younger adults while performing a cognitive task with a narrow base of support. Their findings align with the *Posture First Principle,* which suggests that when undergoing a cognitive-motor dual-task, older adults allocate more resources towards the balance task than the cognitive task especially in situations of increased postural threat to avoid falling. Such prioritization often results in impaired performance on the cognitive task (Shumway-Cook et al., 1997). Similar findings by Swan et al. (2004) demonstrated that while older adults performed a secondary cognitive task, postural sway decreased. This decrease occurred when the balancing conditions were the most difficult. Their explanation for the improvement was related to balance related cues. As such, when balancing becomes challenging, participants increasingly attend to balance-related cues which leads to over-responding. The addition of a secondary task can distract participants from paying close attention to such cues, resulting in reduced sway.

Another potential factor leading to decreased sway during dual-tasks is arousal which was proposed in a study by Brown et al. in 2002. Their study revealed that the *Posture First Principle* was exclusive to older adults. As postural threat increased older adults' postural stability improved, while performance in the secondary spatial letter tasks deteriorated. Interestingly, younger adults showed improvements in the postural and cognitive tasks under increased postural threat. The authors suggest physiological arousal may play an important role in performance discrepancies. Measurements of galvanic skin conductance revealed arousal increased in both younger and older participants in conditions of postural threat. These findings suggest that arousal can be beneficial in preserving and improving stability. However, only younger adults would display cognitive benefits due to increased arousal. Another way of interpreting the results is that the dual-task requirements did not exceed the cognitive capacities of the younger adults like it did the older adults, supporting the findings that reduced cognitive capacity is a function of age. Improved postural control resulting from increased arousal was also suggested by Andersson et al. (2002) where they showed calf muscle stimulation in younger adults compromised body sway during a static balance task, yet the addition of a cognitive task resulted in decreased sway with and without muscle stimulation. They proposed the focus of attention on the cognitive task decreased the difference in sway between counting backwards and just performing a static balance task. Potentially the dual-task may have increased arousal in comparison with the single balance task resulting in postural improvements.

Verbal articulation has been put forward as yet another factor affecting postural performance during dual-tasks. For example, during a subtraction task, participants are required to state their answers out loud. As such, Dault et al. (2003) examined if articulation was contributing to changes found in postural sway. In their study, younger adults stood on a force platform while performing a series of secondary cognitive tasks (silent performance vs. verbal response). Tasks requiring articulation resulted in more pronounced increases in postural sway frequency and sway path than tasks completed with no articulation. These findings suggest that changes in postural stability may result from motor requirements of the task (i.e., speaking) rather than a competition of attentional resources. Yardley et al. (1999) found supporting evidence that oral responses during standing worsened postural performance.

Within the literature, studies surrounding dual-task research are diverse in their experimental designs. Although the literature on the effects of dual-task performance does consistently show that older adult's postural control is more negatively affected than younger adults (Maylor & Wing, 1996) many studies do not take sensory or cognitive deficits into account, which is problematic given their high prevalence rates in older adulthood (see above). It is likely that factors such as sensory functioning and cognitive decline also influence the relation between postural control and cognition in addition to cognitive task demands and age.

Hearing Loss and Postural Stability

Hearing loss among other sensory impairments has shown to be associated with increased instability, difficulties walking, and falls risk (Agmon et al., 2017; Lin & Ferrucci, 2012). For example, Lin and Ferrucci (2012) found that with every 10-dB increase in hearing loss, an individual was 1.4 times more likely to have reported a fall within the 12 preceding months. Approximately 13% of adults 40–49 years of age experience some form of hearing loss, whereas almost 45% of older adults aged 60–69 years live with hearing loss. The prevalence continues to increase to 90% for adults 80 years and older (Goman & Lin, 2016). Hearing loss that occurs as a function of age is characterized by an elevated hearing threshold (i.e., volume at which a sound can be detected) and reduced speech perception such as having troubles detecting, identifying, and localizing sounds, especially in noisy or complex listening environments (Gates & Mills, 2005). This hearing loss is caused by loss of inner and outer hairs cells located in the cochlea which are responsible for encoding high frequency information and transmitting acoustic information to the brain. The loss of these hair cells consequently contributes to the loss of high frequency hearing, resulting in increased hearing thresholds and altered neural processing of auditory input (Peelle & Wingfield, 2016). Researchers have documented a series of modifiable and non-modifiable risk factors associated with this hearing loss such as, cochlear aging (individual age), environment (occupational and leisure noise exposure), ototoxic medications (e.g., antibiotics), socioeconomic status, genetic predispositions (sex, race, genetics), and health co-morbidities (hypertension, diabetes, stroke) (Yamasoba et al., 2013). Age-related and other hearing losses are among the top eight chronic diseases and injuries which alone affected more than 10% of the world's population in 2015 making it a worldwide health concern (Vos et al., 2016).

The association between hearing loss and postural control is often explained by changes to the vestibular system. Whereas changes in the inner ear of the cochlea can cause hearing loss, deterioration of the vestibular system is responsible for changes in balance (Agmon et al., 2017). Vitkovic et al. (2016) demonstrated that vestibular patients had higher centre of pressure path lengths compared to those who had normal balance, and those with greater vestibular deficits derived greater postural benefits from hearing aids. Maheau et al. (2019) found support for Vitkovic's claims and added that the degree of improvement in postural control for individuals with hearing impairment may be linked to vestibular function. However, evidence by Lin and Ferrucci (2012) showed that when controlling for vestibular function, the relationship between hearing loss and falls remained.

Another way to account for the association between hearing loss and postural control is through cognitive load and resource sharing (Lin & Ferrucci, 2012). With age, there is an increase in shared resources, therefore auditory functioning and posture rely on cognitive resources to compensate for peripheral changes (Li & Lindenberger, 2002). However, aging is associated with declines in cognitive abilities such as executive functioning (Head et al, 2002; Murman, 2015) and dividing attention (Fraser & Bherer, 2013; Yogev-Seligmann et al, 2008). Among older adults with auditory and visual impairments, the increased cognitive effort required for auditory and visual processing results in sensory loads taking attentional resources away from behaviors used to maintain balance which can increase falls risk (Doumas et al., 2008). Additionally, Golub (2017) suggested in situations which challenge listening, portions of the brain not involved in auditory processing are activated. This can lead to fewer cognitive resources left for other tasks such as postural control.

Cognition and Hearing Loss

The “cognitive load,” “cascade,” and “sensory deprivation” hypotheses have all been postulated to explain the relationship between sensory impairment and cognitive performance. The cognitive load hypothesis theorizes that hearing loss results in degraded auditory signals which leads to an increase in cognitive resources for auditory processing. This diversion of cognitive resources towards audition and listening effort results in a depleted cognitive reserve. Over time it is expected that the excessive amounts of cognitive load dedicated towards auditory processing can lead to structural brain changes and neurodegeneration (Uchida et al., 2019). However empirical support for this hypothesis is limited.

Given that hearing loss has shown to be associated with a higher risk of MCI and dementia (Livingston et al., 2020), accelerated cognitive decline (Lin et al., 2013), and reduced memory and executive functions (Lin et al., 2011), the cascade hypothesis suggests hearing loss affects brain structures directly via impoverished sensory input (Uchida et al., 2019). Research has demonstrated hearing loss is associated with smaller brain volume and that hearing impairments cause accelerated rates of brain atrophy (Lin et al., 2014; Rigters et al., 2017). In accordance with the cascade hypothesis, hearing loss may result in long-term auditory deprivation, resulting in increased cognitive decline, therefore the use of hearing aids should be associated with better cognitive performance (Dawes et al., 2015). In support of this hypothesis, Dawes et al. (2015) found hearing aid use was positively associated with better cognitive functioning, suggesting cognitive benefits were a result of the direct increase in audibility of sounds in daily life. Similarly, Castiglione et al. (2016) found that after auditory rehabilitation (i.e., cochlear implants and hearing aids) patients displayed improvements in short-term and long-term memory. However, van Hooren et al. (2005) found conflicting evidence whereby hearing acuity improved after a 12-month intervention, but there were no positive effects on cognitive performance (i.e., memory, attention, executive functioning). They proposed that hearing aids only compensated for the impairment at the level of the sensory input system and did not contribute to an improvement in information processing mechanisms. It was speculated, that perhaps benefits of hearing aid use are only evident after 12 months. Fortunately, research by Sarant et al. (2020) demonstrated significant improvements in cognitive function among older males and females after 18 months of receiving a hearing aid fitting. Participants who used their hearing aids greater than 90% of the time demonstrated larger improvements in executive function compared to those who used them less than 90%. Sex differences were observed where, females used their hearing aids more regularly and for longer than did males (56.3% vs. 33.3%), and therefore significantly greater cognitive improvements were observed for females in working memory, visual attention and visual learning (Sarant et al., 2020).

Given the evidence there appears to be more long-term benefits of wearing hearing aids, yet hearing therapies are often underutilized. Based on data from the United States, among individuals 50 years and older with hearing loss, one in seven use hearing aids. These numbers decrease to 1 in 20 for those aged 50-59 years (Chien & Lin, 2012), and among adults aged 70 and older with hearing loss who could benefit from hearing aids, fewer than 1 in 3 (30%) has ever used them (National Institute on Deafness and Other Communication Disorders, 2014). Common reasons for this low adoption rate include financial concerns, lack of knowledge (e.g., beliefs about ineffectiveness in noisy environments), cosmetic appeal, discomfort, etc. However, stigma remains one of the major factors inhibiting hearing aid adoption (David & Werner, 2016; McCormack & Fortnum, 2013; Wallhagen, 2010). The low hearing aid adoption may have many negative consequences on cognitive functioning as explained by the sensory deprivation hypothesis which states that the prolonged absence of stimulation (sensory input) will result in cognitive deterioration due to neuronal atrophy (van Hooren et al., 2005; Valentijn et al., 2005). Empirical support for this hypothesis was reported by Clay et al. (2009), who demonstrated that lower levels of sensory functioning were associated with age-related declines in cognitive speed of processing (Clay et al., 2009). Considering the evidence provided, there appears to be a strong relationship between sensory and cognitive functioning, which when impeded can have repercussions on postural control. Yet, hearing loss is not the only form of sensory loss commonly encountered throughout aging, therefore it critical to consider the role of vision loss on postural control.

Vision and Postural Stability

Visual sensory information is another critical part of postural control. Research suggests that central and peripheral vision are essential in the control of posture. For example, the “peripheral dominance theory” emphasizes that peripheral rather than central vision is essential for postural control. Results from Berensci et al. (2005) support this hypothesis where they found improvements in postural stability occurred with peripheral visual stimulation whereas when a visual stimulus was presented to the central visual field sway increased. Their results indicate a greater contribution of peripheral vision to the control of quiet standing than central vision, consistent with the peripheral dominance hypothesis (Berencsi et al., 2005). The “retinal invariance” hypothesis suggests that both central and peripheral vision are equally important in maintaining postural control (Bardy et al., 1999). The “functional sensitivity” hypothesis, proposes central and peripheral vision have different functional roles that aid in the regulation of postural control (Nougier et al., 1997). More specifically this hypothesis argues that peripheral vision is predominant in antero-posterior control, while central vision predominates medio-lateral control (Agonstoni et al., 2016). Research by Nougier et al. (1997) found supporting evidence for this hypothesis where central and peripheral vision equally regulated posture when somatosensory information was not altered. Each of the visual modalities contributed to the regulation of posture using different kinds of optical information. When body sway increased as a result of alterations to somatosensory information, peripheral vision was more efficient in stabilizing antero-posterior sway, whereas central vision was more efficient in stabilizing medio-lateral sway.

Given vision is critical in maintaining posture, and commonly declines as a function of age (Haegerstrom-Portnoy et al., 1999) the literature linking vision loss and posture is vast. By 75 years of age, 50% of Canadians have vision loss (Mick et al., 2021) and vision loss has been associated with disability, impaired daily functioning and a higher risk of falling (Dolinis et al., 1997; Lord & Menz, 2000; Ramrattan et al., 2001). A large population-based study of older adults between the ages of 72 and 92, demonstrated that age-related vision loss was associated with a decline in mobility indices such as walking speed and erroneous contacts during obstacle avoidance tasks (Turano et al., 2004). Results from Choy et al. (2003) reveal that with advancing age adults rely more heavily on vision. Instability was evident among 40-, 50- and 60-year-old women who relied on vision for postural stability during a series of balance conditions. For example, in comparison to 20- and 30-years old's, under conditions involving eyes closed, women in their 40s were more unstable during single-limb stance, from the 50s when bilateral stance on foam was tested, and from the 60s when a firm surface was used. However, for women in their 20s and 30s there were no significant differences in balancing ability when vision was manipulated.

Research has demonstrated reduced postural stability in individuals with true visual impairments and among those with simulated visual impairment (Black et al., 2008). It has been well documented that individuals with Age-Related Macular Degeneration have poor postural stability compared to healthy controls displaying higher anterior-posterior centre of pressure displacements especially in eyes closed situations (Chatard et al., 2017). Ray et al. (2008) compared sighted individuals with a visual acuity above 20/200 (legal blindness) to participants with a visual acuity less than 20/200 all of whom were between the ages of 20-55 years. Postural evidence displayed poorer postural control among those with vision loss (20/200) especially in conditions which required responding to floor movements created by sway referencing. These results suggest those with profound vision loss were not able to fully compensate for the role vision plays to maintain postural stability (Ray et al., 2008). Similar results were demonstrated when comparing younger adults ranging from 20-37 years of age, where participants with low-vision presented greater body sway compared with the normal vision during balance on a foam surface (Tomomitsu et al., 2013). Similarly, Black et al. (2008) determined that older adults with glaucoma had reduced postural stability in conditions involving both firm and foam surfaces.

Research using simulated vision impairment goggles has identified increased postural instability, specifically anterior-posterior changes in older adults (Hallot et al., 2020). Another study investigating the effects of simulated refractive blur on postural stability in healthy older adults found increases in postural instability under normal and quiet standing conditions. Disruptions of the somatosensory system and vestibular systems alone increased postural instability. However, the greatest postural instability arose when the inputs from somatosensory and vestibular systems were present (Anand et al., 2003). Given that the visual system plays a major role in postural control and is subject to decline with aging (Tomomitsu et al., 2013), it becomes increasingly important to screen and treat visual impairments to maintain posture and decrease falls risk.

Cognitive Decline and Postural Stability

Aside from experiencing sensory loss, cognitive decline is another commonly encountered condition in older adulthood and evidence depicts a relationship between Mild Cognitive Impairment (MCI) and postural control. MCI affects between 15% and 20% of persons 60 years and older (Petersen, 2016). This condition is defined as an intermediate state between normal aging and dementia (Chen et al., 2018) and is categorized as “cognitive decline greater than expected for an individual's age and education level but that does not interfere notably with activities of daily life” (Gauthier et al., 2006, p. 1262). Patients with this condition have mild but measurable changes in their cognition and memory which are noticeable to the person affected and those around them. Individuals diagnosed with MCI may remain stable, return to normal, or progress to dementia (Chen et al., 2018; Gauthier et al., 2006; Mitchell & Shiri-Feshki, 2009). It has been supported that a decline in cognitive abilities can lead to increased risk of difficulty in performing daily living activities (Willis et al., 2006). Even more concerning is older adults with cognitive impairments and dementia are at double the risk of falling compared to age-matched healthy older adults (Shaw et al., 2003). There is evidence to support the findings that there is a specific deficit in balance control in MCI patients compared with controls (Shin et al., 2011). For example, older adults with MCI demonstrate greater mediolateral sway than their cognitively normal counterparts (Shin et al., 2011). A review and meta-analysis of 14 studies found that static balance was affected by MCI. More specifically MCI impacted medial lateral and anterior-posterior sway in the condition with eyes open, suggesting cognitive changes impact postural control. Bahureksa et al. (2017) suggest people with MCI have deficits in central processing of visual information which results in increased anterior-posterior postural sway during balance testing. However, Shin et al. (2011) found anterior-posterior sway speed and distance did not differ between those with MCI and healthy controls (Shin et al., 2011). Under cognitive-motor dual-task conditions, an increase in the level of dual-task interference has been observed in older adults with MCI or a history of falls (Hauer et al., 2003). Further research in this field can potentially help identify which balance parameters are more sensitive to MCI which can aid in early MCI discrimination (Bahureksa et al., 2017).

Multisensory Loss

As mentioned throughout, an individual's ability to maintain posture efficiently is heavily influenced by the contribution of cognitive functioning and multiple sensory systems (i.e., proprioceptive, vestibular, auditory) (Seidler et al., 2020). There is an abundance of evidence to suggest that increased cognitive load (Pellecchia, 2003), vision (Reed-Jones et al., 2013) hearing (Lin & Ferrucci, 2012) and cognitive impairments (Shin et al., 2011) alone impact balance. Much less well understood is the impact of cognitive load and multisensory impairments on balance and falls despite nearly one fifth of older adults reporting dual-sensory loss (Brennan et al., 2005). Results from Brennan et al. (2005) suggest and that both the number, and the degree of dual-sensory impairments influence participants' performance on a series of activities of daily living (ADLs). Furthermore, some research suggests an individual's risk of mortality increases because of dual-sensory loss (Gopinath et al., 2013). Therefore, dual-sensory loss may exacerbate the decline in functioning in older adults, as they no longer can compensate for the loss through greater recruitment of other senses (Saunders & Echt, 2007).

Research surrounding dual-sensory loss has demonstrated hearing and vision loss are positively associated with several measures of postural control. Additionally, evidence supports the findings that multiple sensory impairments increase the odds of both reporting difficulty with falls and balance dysfunction (Wilson et al., 2016). During dual-tasks, researchers have established that individuals with central vision losses (Kotecha et al., 2013) or MCI (Hauer et al., 2003) exhibit greater instability with the addition of a secondary cognitive task whereas balance seems to be prioritized over cognitive performance in older adults with hearing loss in the presence of a noisy environment (Bruce et al., 2019). Yet, it is still unclear how combinations of increased cognitive load, cognitive decline, and multisensory loss impact older adult's postural stability.

Multisensory loss has also seen to negatively impact cognitive functioning, in that with every additional sensory impairment, there is a notable decrease in measures of cognitive performance, such as short-term memory and decision making (Yamada et al., 2016). Additionally, Davidson and Guthrie (2017), discovered that among their sample of older adults, the poorest cognitive performance was found in individuals with both hearing and vision loss. Cognitive impairment is therefore more prevalent in older adults with multiple sensory impairments as compared to those with single sensory impairments (i.e., hearing or vision loss) (Mitoku et al., 2016). Furthermore, dual-sensory loss has shown to have a greater risk of developing dementia as compared to zero or single sensory impairments (Brenowitz et al., 2018).

Summary and Current Study

Given the interconnections between hearing, vision, cognition, and motor domains, it is evident that postural control is subject to decline because of decrements in other sensory-cognitive domains (Woollacott & Shumway-Cook, 2002). Decrements in stability have shown to increase falls risk among older adults resulting in hospitalizations (Statistics Canada, 2016) and mortality (Public Health Agency of Canada, 2014). It is therefore critical we expand our research focus towards understanding the role of dual-sensory loss on posture to preserve healthy aging and reduce falls risk.

As described above, postural control appears to be greatly influenced by cognitive load (Huxhold et al., 2006) sensory loss (Wilson et al., 2016) and experimental designs consisting of verbal articulation (Dault et al., 2003), point of fixation (Kapoula and Lê, 2006), and type of secondary cognitive task (i.e., visual search, counting backwards, visuo-verbal Stroop) (Condron & Keith 2002; James et al., 2004; Kapoula and Lê, 2006). However, fewer experimental designs have considered these factors in combination. To address this omission, the current research uses a dual-task design which mimics the reduced cognitive capacity of older adults and use goggles to simulate age-related vision loss. Categorization of older participants into normal and hearing loss sub-groups allowed the consideration of auditory status as a potential moderator of younger and older adults' cognitive-motor dual-task performance.

Being that older adults have fewer cognitive resources available for dividing attention and compensating for sensory deficits, they are more likely to display postural instability especially during dual-tasks (Woollacott & Shumway-Cook, 2002). Therefore, the purpose of the current project was to address how increased cognitive load and simulated vision loss influence younger and older adults' single- and dual-task performance. The recruitment strategy taken for the older adults was more inclusive than the usual recruitment from existing participant pool lists. As such, older adults were not excluded due to hearing impairment or low cognitive status. This enabled a consideration of the moderating effects of hearing impairment and suggestive MCI on older adults' dual-task performance. The following hypotheses were investigated:

1) We hypothesized that as task complexity increased (i.e., vision challenge and/or cognitive load), postural control would decrease in both younger and older adults

2) We hypothesized that as task complexity increased, there would be differences in postural control between the three groups. We expected older adults with hearing loss to exhibit the greatest postural control decrements (i.e., increase in instability), followed by older adults without hearing loss, while the younger adults would display the smallest decrements.
3) In accordance with the foregoing literature review, we expected all three groups to display positive dual-task postural costs. Under normal vision conditions, older adults with hearing loss would display the largest costs, while the younger adults would display the lowest. Under low vision conditions, older adults with hearing loss would display the fewest costs, while the other older adult group would show the largest costs.
4) Regarding cognitive dual-task costs, we hypothesized that all three groups would display positive dual-task costs. Under normal and low vision conditions it was expected that the largest costs would be among the older adult hearing loss group, followed by the older adult normal hearing and younger adult groups.
5) We hypothesized participants with low cognitive status and hearing loss would have the largest increases in instability as balance task complexity increased, compared to older adults without such impairments.

Methods

Participants

Data were collected from 27 older adults between the ages of 56 and 93 years (*M* = 74.74 *SD* = 9.50), and 32 young adults between the ages of 19-34 years (*M* = 23.03 *SD* = 3.53). The older adults were split into two groups based upon hearing acuity (i.e., normal hearing vs. hearing impaired). The older adult sample consisted of 11 older adults with no hearing loss (< 25 db HL: *M* = 71.27 *SD* = 11.30) and 16 older adults with hearing loss (*M* = 77.13 *SD* = 7.53). Among the 16 hearing impaired adults, 5 had moderate hearing loss (41–60 dB HL), and 11 had mild hearing loss (26-40 dB HL). Five older adults utilized assistive devices.

Older adults were recruited during a 3.5-week research residency at the engAGE Living Lab, located in a shopping mall in Côte St.-Luc, Quebec. The Living Lab is an interactive space to help older adults combat social isolation while also taking part in collaborative research. An advertisement of the study which read "Check Your Balance" ran on a Television screen in the Living Lab, therefore participants interested in the study could walk in, sign up and take part immediately. The residency allowed for data to be collected in a natural setting, allowing for a more diverse aging population to be recruited. Participants were included if they were 50 years or older and had normal or corrected-to-normal vision. Participants were excluded if they reported any known vestibular disorders, artificial limbs, or any neurodegenerative diseases (e.g., dementia). The younger adults were recruited via the Concordia Participant Pool, whereby participants would sign up in advance through an online portal. Younger adults were tested in the Adult Development and Cognitive Aging Laboratory at Concordia University. Those who took part received one participant pool credit (.5%) which they could put towards a Concordia psychology course involved in participant pool research. Young participants were included if they were between the ages of 18-35 years, and had normal or corrected-to-normal vision. Young participants were excluded if they reported any cognitive impairments, vestibular disorders, or artificial limbs.

Measures

Demographics. All participants filled out a General Health Questionnaire which asked about age, gender, falls history, and any injuries related to their fall's history. Additionally, participants specified if they had any previous or current head injuries, chronic dizziness, other medical health conditions (e.g., high blood pressure, glaucoma, diabetes, etc), factures below the waist, medication history, and if they used an assistive device.

Cognitive Functioning. The Montreal Cognitive Assessment (MoCA: Nasreddine et al., 2005) was used as a measure of global cognition, rather than a screening tool for exclusion purposes. The MoCA is comprised of eight sections, each assessing a different domain of cognitive functioning. More specifically the test includes the categories of visuospatial/executive naming, attention, language, abstraction, delayed recall, and orientation. The total available points are 30, and participants were given an extra point if they had less than 12 years of education. A lower score on the MoCA indicates poorer cognitive performance. More specifically, a score of less than 26 is suggestive of the presence of MCI. The MoCA has a good internal consistency, with a Cronbach alpha of 0.83 (Nasreddine et al., 2005). The duration of the test was approximately 10 minutes. Participants with MoCA below 26 remained eligible for the study.

The Serial 7s subtraction task (single-task: Wechsler,1955) was used as a measure of working memory. During this task participants remained in a seated position wearing clear goggles as a control, while fixating on a target icon on the wall in front of them. Participants were required to count backwards by 7s from 175 for 30 seconds. Participants gave their answers verbally and the number of correct responses was recorded and used as an indicator of single-task cognitive performance. In the case of a calculation error, participants were permitted to continue and the correct subtractions from that point onward were recorded as valid.

Vision. The Freiburg Visual Acuity Test (Bach, 1996) was used to assess binocular visual acuity. This computerized acuity test uses Landolt Cs presented in one of four orientations (up, down, left, right). Participants are asked to identify which direction the gap of a Landolt C is presented. The letter size would change after each trial using an adaptive procedure to assess the smallest stimulus detected. A total of 24 trials was administered. The program was calibrated by entering information pertaining to observer distance (140 cm), and the width of the active display area (170 mm). For this study participants sat in a chair 140 cm away from the computer screen which was stationed at eye level. During this task participants wore normal corrected (clear) vision goggles over their eyes or if needed over their eyeglasses. Upon the presence of each individual Landolt C participants verbally gave their response, while the researcher inputted their answer via a computer keyboard. This task took approximately two minutes. Visual acuity scores were documented.

Audition. ShoeBOX Audiometry (Clearwater Clinical Limited, Ottawa, ON) an interactive play audiometer for the Apple® iOS platform was used to measure both younger and older adults hearing acuity. ShoeBOX Audiometry is clinically validated for auditory assessment outside of a sound attenuated booth (Bastianelli et al., 2019). Specially calibrated DD 450 Headphones were used to deliver pure tones, which ranged in frequency (e.g., 200, 500, 1000, 2000, 3000, 4000, and 8000 Hz) with a minimum volume of 10 dB and maximum volume of 85 dB. Participants with hearing aids were instructed to remove them before beginning the hearing test. During the test, pure tones were presented to the right ear first followed by the left ear. Participants responded using a touch-sensitive tablet. During the auditory assessment participants were instructed to touch a blue disk appearing on the tablet screen to hear a tone. Touching the disk would give off a tone 50% of the time. Depending on whether or not a tone was heard participants would drag the blue disk to the green "heard" speaker or the red "not heard" speaker. A total of 70 trials was completed (35 per ear). ShoeBOX contains a function to correct for noise in the testing environment and flag unreliable responses. Given that ShoeBOX Audiometry has been validated against standardized pure tone testing methods it was chosen to facilitate the unconventional setting of our testing locale in the Living Lab. Using the World Health Organizations guidelines for classifying hearing impairments, participants were classified according to the grades of hearing acuity which were calculated using pure tone averages (PTA) for the better ear as an average of four frequencies (e.g., 500, 1000, 2000, 4000 Hz) (World Health Organization, 1991). As recruitment for this project did not involve actively seek out older adults with hearing impairments, two broad categories of hearing status were created: PTAs above 25 dB HL indicated those with hearing loss, while PTAs below 25 dB HL was indicative of those with healthy hearing. A higher pure tone average (PTA) would indicate poorer hearing acuity, that is a greater sound intensity (dB HL) would be needed to exceed the threshold of tone detection (Yeung et al., 2015).

Balance Confidence. Participants completed an Activities-specific Balance Confidence (ABC) Scale (Powell & Myers, 1995), a subjective measure of balance. This scale requires participants to indicate how confident they are in their balance abilities when performing certain tasks on a scale of 1 (not confident) to 100 (completely confident). This scale has been designed to target community-dwelling older adults and covers a range of daily activities which vary in their level (Cronbach alpha = 0.95: Talley et al., 2008).

Postural Stability. A Nintendo Wii Balance Board (WBB: Nintendo, Kyoto, Japan) was paired with custom software (RombergLab) that recorded a series of balance parameters (Martinez & Fernandez, 2016) to assess static balance. RombergLab software was downloaded on a MacBook Air computer (Apple Inc, CA, USA) and connected via bluetooth to the WBB. The WBB was calibrated at the beginning of each trial. Similar to typical force plates the WBB contains four gauge-based load sensors. The average sampling frequency of the board was around 40 Hz which is lower than that reported in the literature (Audiffren & Contal, 2016; Pagnacco et al., 2010). The WBB is considered to be a reliable and valid tool for assessing standing balance with excellent concurrent validity for static balance assessment in healthy and clinical populations when compared with other force platforms (Clark et al., 2018).

To characterize postural control, the following centre of pressure (COP) measures were considered for each trial: Total Centre of Pressure displacement (mm), which is the total distance travelled in millimetres; Medial-Lateral sway amplitude (mm), the distance between the farthest point leftward and rightward; Anterior-Posterior sway amplitude (mm), the distance between the most forward and backward point; Total Path Velocity (mm/s) which was obtained by dividing the total path length by the duration of quiet standing per trial. These outcome variables were determined using the analysis techniques contained in SeeSway, an online calculator incorporating MATLAB and LabVIEW software (Clark & Pua, 2018).

Participants were required to complete five static balance conditions which varied according to cognitive and visual load. For each condition participants were asked to "stand as still as possible" for a duration of 30 seconds. The first condition involved a manipulation of vision where participants balanced with their eyes closed. Two other conditions incorporated the use of a sensory challenge using simulated vision loss goggles (visual acuity of 20/80). The vision impairment goggles were designed to mimic the visual acuity of an individual with low vision loss and were worn over participants who had glasses. A simulated visual acuity of 20/80 was chosen as it is the level of visual impairment needed to qualify for vision rehabilitation in Quebec. Participants first balanced with low vision goggles, then they completed this same task again while simultaneously counting backwards by 7 from 350. Two balance conditions did not involve a visual manipulation, therefore clear control goggles were worn. Again, participants completed a static balance task with the control goggles and again while concurrently counting backwards by 7 from 200. The five static balance conditions were therefore as follows: Eyes closed, single-task normal vision, dual-task (serial 7s) normal vision, single-task low vision, dual-task (serial 7s) low vision. These conditions were used to determine how both a sensory challenge and a cognitive load influenced the centre of displacement measures (i.e., path length, amplitude, path velocity). To account for potential learning and fatigue effects, the order of the balance test conditions was counterbalanced.

General Procedure

Prior to participating, individuals were required to sign a consent form. They were instructed of their rights, and their ability to discontinue at any point throughout the study. The General Health questionnaire was administered first, followed by the Activities-specific Balance Confidence Scale, then the MoCA (MoCA was only administered to older adults). Upon their completion, hearing acuity, vision tests, and the single cognitive task (serial 7s) were measured in that order respectively. The testing ended with the 5 static balance conditions. Once all the measures were completed, participants were debriefed, and contact information was provided in the case of follow up questions from the participants. Total time to complete all experimental measures was 25 minutes per participant.

Data Screening

Prior to conducting the statistical analyses, the data were examined for outliers, skewness and kurtosis. Specifically, descriptive statistics were assessed. Raw scores for balance measures were converted to z-scores and inspected to ensure that they fell within three standard deviations of the mean. Data from 29 older adults and 33 older adults were collected, however two older adults and one younger adult were removed from data analyses. One older adult was unable to finish all five balance conditions, and hearing thresholds indicated they had profound hearing loss, therefore their data were removed from the dataset. Another older adult exceeded three standard deviations on all four postural parameters scores across all five balance conditions, therefore their data were excluded. One younger adult had their data excluded as they did not follow instructions to stay stationary on the balance board, which resulted in heightened anterior-posterior amplitude and path velocity scores which were outside the three standard deviation cut off across all 5 balance conditions. After removing these three participants from the analyses, the final sample size was 27 older adults and 32 young adults.

There were no missing values within the final dataset. To check the normality of each variable, Skewness and Kurtosis were assessed. Using suggestions from Kline (2011), an absolute value of Skewness greater than three and Kurtosis value greater than 10 may indicate a problem and values above 20 may indicate a more serious problem. Based on this recommendation the absolute values of the Skewness and Kurtosis of all the balance measures in this study were determined to be within the acceptable range of < 3 and < 10, respectively. More specifically, the highest values of Kurtosis found were in two eyes closed conditions: Medial Lateral Amplitude (3.18) and Anterior Posterior path velocity (3.34). However, because skewness and kurtosis are both not equal to 0 we cannot conclude that the distribution is normal, therefore the distribution is not severely non-normal (Kline, 2011).

The assumptions needing to be met to conduct a mixed analysis of variance (ANOVA) and independent sample t-tests were also considered. The assumption of independence was met, indicating that the sample was both randomly and independently sampled. Regarding the repeated measures ANOVA, Mauchly's test of sphericity was significant, therefore the results were interpreted using a Greenhouse-Geisser correction. Regarding independent samples t-tests, Levene's test for equal variances was significant, and we therefore interpreted the results using equal variances assumed.

Results

Baseline Group Differences

Means and standard deviations for all the measures employed in the current study are presented in Table 1. There were significant age differences between groups, more specifically when comparing the younger adults (YA) to older adults with hearing loss (OAHL) and older adults with normal hearing (OANH: *p*s < .0001). An independent samples t-test showed that the age difference between the older adult groups was not significantly different $t(25) = -1.62$, $MD = -5.86$, $SE = 3.61$, 95% CI [-13.29, 1.59], $p = .118$. Additionally, younger adults had significantly better balance confidence scores and visual acuity compared to the two older adult (OA) groups. Group differences in decibels of hearing loss (dB HL) were also apparent, where younger adults displayed the lowest dB HL, followed by the OANH group, with the OAHL group demonstrating the largest dB HL. One older adult from the hearing loss group utilized hearing aids. Finally, no YAs used walkers whereas, 3 OAHL and 2 OANH did.

To account for differences in learning and fatigue effects during the balance tasks we randomly assigned participants into two groups. All groups started with the eyes closed balance condition, then one group carried on with the normal vision single- and dual-tasks followed by the low vision single- and dual-tasks. The other group carried on with the low vision tasks ending with the normal vision tasks. There were no statistical differences in balance or cognitive scores between the counterbalanced groups, meaning differences in learning and fatigue effects were not evident ($p < .05$).

To evaluate the effect of increasing task complexity on postural control, we conducted a 3 x 5 mixed analysis of variance (ANOVA). Specifically, the within-subjects factor was Task Complexity with 5 levels (normal vision single and dual-task (serial 7s), low vision single- and dual-task and eyes closed). We used three groups as a between-subjects factor: YA, OANH, OAHL. A post-hoc power analysis (i.e., observed power) for detecting a group by task complexity interaction effect for each balance parameter using a Greenhouse-Geisser correction was as follows: total path length .978, medial-lateral amplitude .929, anterior posterior amplitude .999, total path velocity .955.

Hypothesis 1

It was hypothesized that as task complexity increased (i.e., presence of a low vision and/or cognitive load) postural control would decrease (i.e., increase in instability). Statistically significant main effects of task complexity were observed for total path length (mm) $F(1.92, 107.52) = 21.54$, $p < .0001$, $\eta_p^2 = .278$), medial-lateral amplitude (mm) $F(2.12, 118.43) = 11.70$, $p < .0001$, $\eta_p^2 = .173$, anterior-posterior amplitude (mm) $F(2.26, 149.10) = 29.32$, $p < .0001$, $\eta_p^2 = .344$, and total path velocity (mm/s) $F(1.92, 107.49) = 21.55$ $p < .0001$, $\eta_p^2 = .278$. See Tables 2A-2D. These results indicate that as task complexity increased, postural control decreased (i.e., instability increased).

Data for all complexity conditions are shown per balance parameter in Figure 1A-1D. Post-hoc pairwise comparisons using Bonferroni corrections were used to identify which balance conditions differed specifically from one another. We found that using the normal vision single-task balance condition as a reference point, total path length increased with the addition of a cognitive load (i.e., normal vision dual-task: *MD* = -242.83, *SE* = 31.53, 95% *CI* [150.63, 335.00], $p < .0001$) with the addition of visual challenge (*MD* = -98.54, *SE* = 28.30, 95% *CI* [-181.23, -15.84], $p = .010$), a visual and cognitive challenge (*MD* = -277.87, *SE* = 31.07, 95% *CI* [-368.69, -187.06], $p < .0001$) and the removal of a visual modality (eyes closed: *MD* = -381.30, *SE* = 57.62, 95% *CI* [-549.69, -212.91] *p* < .0001). Medial-lateral amplitude increased as a result of task complexity when comparing normal vision single-task to the normal vision dual-task (*MD* = -13.22 , *SE* = 3.01, 95% *CI* [-22.02,-4.41], *p* < .0001), low vision dual-task (*MD* = -7.60, *SE* = 1.67, 95% *CI* [-12.50, -2.71], *p* < .0001) and an eyes closed condition (*MD* = -12.90, *SE* = 2.05, 95% *CI* [-18.90, -6.90], *p* = .0001). However, the addition of a single-task low vision challenge itself did not result in significant differences from the baseline condition (*MD* = -1.75, *SE* = .862, 95% *CI* [-4.27, .767], *p* = .468). Anterior-posterior amplitude increased significantly when comparing normal vision single-task to the normal vision dual-task (*MD* = -12.57, *SE* = 2.34, 95% *CI* [-19.41, -5.74], *p* < .0001), low vision single-task (*MD* = -6.24, *SE* = 1.40, 95% *CI* [-10.30, -2.19], *p* < .0001), low vision dual-task (*MD* = -17.20, *SE* = 2.57, 95% *CI* [-24.70, -9.70], *p* < .0001), and eyes closed (*MD* = -28.32, *SE* = 2.80, 95% *CI* [-36.50, -20.14], *p* < .0001). Similarly, total path velocity also increased significantly when comparing the normal vision single-task to the normal vision dual-task (*MD* = -8.10, *SE* = 1.05, 95% *CI* [-11.17, -5.02], *p* < .0001), low vision single-task (*MD* = -3.29, *SE* = .94, 95% *CI* [-6.04, -.53], *p* = .01), low vision dual-task (*MD* = -9.27, *SE* = 1.04, 95% *CI* [-12.29, -6.24], *p* < .0001) and the eyes closed condition (*MD* = -12.72, *SE* = 1.92, 95% *CI* [-18.34, -7.11], *p* < .0001). Taken together, as task complexity increased, postural decrements (increase in total path length, total path velocity, medial-lateral and anterior-posterior amplitude) were evident aside from the low vision single-task for medial-lateral amplitude.

Hypothesis 2

The second hypothesis considered differences between groups (YA, OANH, OAHL). We hypothesized that as task complexity increased, there would be differences in postural instability across the three groups. We expected OAHL to display larger increments in instability than

OANH, with the YAs showing the smallest increases as a function of complexity. Based on the repeated measures ANOVA described above, we found significant interactions of group and balance complexity, for total path length $F(3.84, 107.52) = 5.13.$, $p = .001$, $\eta_p^2 = .155$, medial-lateral amplitude $F(4.23, 118.43) = 5.55$, $p < .0001$, $\eta_p^2 = .165$, anterior-posterior amplitude $F(5.325, 149.10) = 7.17$, $p < .0001$, $\eta_p^2 = .204$, and total path velocity $F(3.84,107.49) = 5.13$, $p = .001$, $\eta_p^2 = .155$. See Tables 2A-2D**.** Together, these results suggest that there were evident group differences in the response to the manipulation of balance task complexity. See Figures 2A-2D.

To examine if the interaction was driven by age, we split the sample into two groups: YAs (19-34 years; n = 32) and OANH (56-90 years; n = 11), removing the OAHL group. We performed one-way ANOVAs for each balance parameter: total path length, total path velocity, media-lateral amplitude, and anterior-posterior amplitude. These tests revealed significant ($p < .0001$) differences between YAs and OANH across all five balance complexity conditions. More specifically, younger adults had better postural control than older adults. See Tables 3A-3D.

Finally, to examine if the earlier 3x5 interaction was powered by hearing status in the older adults, we split the sample into two groups: OAHL (n = 16) and OANH (n = 11) removing the younger adults from the analysis. Again, we performed four one-way ANOVAs for each balance parameter: total path length, total path velocity, media-lateral amplitude, and anterior-posterior amplitude. Results revealed no significant ($p < .05$) differences between the OAHL and OANH groups across any of 5 balance complexity conditions, except for medial-lateral amplitude in the single-task low and normal vision conditions. After computing two independent samples t-tests there were significant differences in medial-lateral amplitude between the groups in single-task normal vision $t(25) = -2.15$, $p =.042$, $d = 0.87$, 95% *CI* [-19.02, -.39]) and single-task low vision conditions $t(22.84) = -2.43$, $p = .023$, $d = 0.90$, 95% *CI* [-19.38, -1.57]). We, therefore, concluded that the interaction was not driven by hearing status and older age**.** See Table 4.

Hypothesis 3

It was hypothesized that all three groups would display dual-task postural costs in both low vision and normal vision conditions. Under the normal vision condition, we expected the highest costs to be among the OAHL group, followed by the OANH group with the YAs displaying the lowest costs. For the low vision condition, we anticipated dual-task costs would increase from the normal vision costs for the OANH and YA group. However, the OAHL group would follow the *Posture First Principle*, as the presence of a low vision and cognitive challenge would threaten balance, resulting in postural prioritization. Therefore, we expected the OAHL group to show a decline in costs from normal to low vision, and also display the least postural costs compared to the other two groups.

Postural Dual-Task Costs. To quantify the postural dual-task costs ($DTC_{posture}$) in each subject for all combination tasks, we used the following formula:

$$DTC_{posture} = 100 \times [(\text{dual-task postural score—single-task postural score})/\text{single-task postural score}].$$

All postural dual-task costs were tested against 0 using one-sample t-tests. Among all three groups the dual-task costs were significantly ($ps < .05$) different from 0, except the OAHL group under the low vision condition for medial-lateral amplitude ($p = .159$), therefore, there was no change in medial-lateral amplitude from the single-task low vision to dual-task low vision condition.

When group differences in postural dual-task costs in total path length, medial-lateral amplitude, anterior posterior amplitude, and total path velocity were considered using one-way

ANOVAs, there were no significant group differences (*p*s > .05) between any of the three groups across any of the normal and low vision dual-task balance conditions. See Figures 3A-3D. However, in partial support of this hypothesis, all three groups demonstrated postural dual-task costs. For example, under total path length the OAHL group presented with 31.84% dual-task costs in the normal vision condition and 17.42% dual-task costs within the low vision condition. Dual-task costs for the OANH group were 26.52% and 26.56% for normal and low vision conditions respectively. Younger adults displayed 26.09% and 32.25% dual-task costs for normal and low vision conditions respectively. See table 5A and 5B for group means and standard errors of normal vision and low vision postural dual-task costs, respectively. Although costs visually appear greater for one group over another there were no significant group differences ($p < .05$) across the four balance parameters, therefore this hypothesis was not supported.

Upon visual inspection alone, it appears younger adults had the largest postural dual-task costs in total path length in the low vision condition, which was opposite of what we anticipated. Within dual-task conditions for total path length the OAHL group appear to allocate more attention to their balance in the low vision condition in comparison to the normal vision condition. A paired sample t-test revealed this result to approach significance, $t(15) = 2.03$, $p = .061$, $d = .51$, 95% *CI* [-.72, 29.54]. Additionally, the OAHL group exhibited significant reductions in medial-lateral amplitude from normal vision to low vision, $t(15) = 2.50$, $p = .024$, $d = .63$, 95% *CI* [13.68, 171.33]. These results suggest the presence of a low vision challenge posed a threat to balance, resulting in allocating more cognitive resources towards preserving medial-lateral amplitude, reducing total path length. However, we found no support for the *Posture First Principle*.

Cognitive Dual-Task Costs. Alternatively, to focus on cognitive performances, we calculated the cognitive dual-task costs ($DTC_{cognitive}$) using the following formula:

$$DTC_{cognitive} = 100 \times [(\text{single cognitive score—dual-task cognitive score})/\text{single score score}].$$

The single-task cognitive score indicates the average number of correct serial 7s subtractions in the seated position, while the dual-task cognitive score indicates the average number of correct serial 7s subtractions during the normal vision and low vision balance tasks.

All cognitive dual-task costs were tested against 0 using one-sample t-tests. Among the OANH group, their costs in normal $t(10) = 3.15$, $p = .01$, $d = .95$, 95% *CI* [6.70, 39.27] and low vision conditions $t(10) = 3.19$, $p = .01$, $d = .96$, 95% *CI* [11.05, 62.12] were significantly different from 0. Among the YA group, their costs under the normal vision condition were significantly different $t(31) = -3.09$, $p = .004$, $d = -.55$, 95% *CI* [-46.18, -9.49] while their low vision costs were not $t(31) = -1.07$, $p = .294$, $d = -.19$, 95% *CI* [-71.92, 22.49]. The OAHL group showed no significant difference from 0 in dual-task costs in both the normal $t(15) = -1.83$, $p = .087$, $d = -.46$, 95% *CI* [-91.45, 6.96], and low vision conditions $t(15) = -1.42$, $p = .177$, $d = -.35$, 95% *CI* [-58.13, 11.73].

Hypothesis 4

Regarding cognitive dual-task costs, we hypothesized that under normal vision dual-task conditions, all three groups would display cognitive costs with significant differences between groups. Under normal vision and low vision conditions it was expected that the largest costs would be among the OAHL group, followed by OANH and YA group. Within groups we expected the OAHL group to show the most significant increases in cognitive costs from the normal to low vision condition, followed by the OANH group as the low vision challenge would threaten posture, resulting in more resources being directed towards posture instead of cognitive performance. We predicted the YAs to show no cost differences from normal to low vision.

Contrary to our expectation, the OAHL group did not demonstrate any costs in normal or low vision conditions. That is, the OAHL group showed no improvements or deterioration in their cognitive performance (i.e., number of correct serial 7s subtractions) in the dual-tasks, compared to the single-task conditions. The fourth hypothesis was therefore not supported. Although upon visual inspection it appears the OAHL group demonstrated cognitive facilitation in both normal and low vision conditions, these values as mentioned above were not significantly different from 0, indicating that the noted small facilitation effect should only be considered a trend.

A one-way ANOVA was conducted to compare the cognitive dual-task costs of OANH, OAHL, and YA groups. Analyses revealed statistical significance between the three groups under normal vision conditions $F(2,56) = 3.91$, $p = .026$, $\eta_p^2 = .123$. A Bonferroni-corrected post hoc test revealed significant differences in cognitive dual-task costs in the normal vision condition when comparing OANH to OAHL (*MD* = 65.23, *SE* = 24.21, 95% *CI* [5.47,124.99], $p = .028$). As such, the OAHL group showed no costs whereas the OANH exhibited positive cognitive dual-task costs. Under normal vision conditions when comparing cognitive costs between OANH to YA the *p*-value approached significance (*MD* = 50.82, S*E* = 21.61, 95% *CI* [-2.51, 104.15], $p = .067$). See Figure 4**.** There was no evidence of significant group differences under low vision conditions, $F(2,56) = 1.52$, $p = .228$, $\eta_p^2 = .05$, therefore this hypothesis was not supported. It was also visually evident that the YA group displayed cognitive facilitation in both normal and low vision conditions. However, the low vision negative cost was not significantly different from 0, therefore the YA group went from displaying facilitation in the normal vision condition to 0 costs in the low vision condition. A paired sample t-test revealed the difference between the two conditions to not be significant $t(31) = -.128$, $p = .90$, $d = -.02$, 95% *CI* [-52.69, 46.46]. This did not support our hypothesis. The OANH group displayed positive costs in both conditions, and the difference was not significant $t(10) = -.880$, $p = .40$, $d = -.26$, 95% *CI* [-48.02, 20.83]. See Table 6 for means and standard errors values for cognitive dual-task costs based on group.

Hypothesis 5

We hypothesized participants with low cognitive status and hearing loss would have the largest increases in instability as balance task complexity increased, compared to older adults without such impairments. There were no significant correlations between MoCA scores and any of the balance parameter outcomes across the five balance conditions. After pooling older adults with hearing loss and MoCA scores below the 26-score cut-off together and comparing them to older adults without hearing loss and normal MoCA scores, independent samples t-test revealed no significant ($p < .05$) differences between the groups. It was therefore concluded that combined cognitive and hearing status did not have an impact on postural control in this sample of older adults.

Results Summary

In summary, we found a main effect of task complexity that is, as task complexity increased, postural control worsened. This effect was especially apparent when using the normal vision single-task balance complexity as a reference point. It was also noticeable that an interaction occurred between task complexity and group. After comparing the YAs to the OANH group, it was evident the interaction was driven by age, such as that the YAs had significantly better postural control, which was expected. Unexpectedly, the interaction was not driven by hearing status when comparing the OANH and OAHL groups. After comparing the OANH group to participants with both MoCA scores below 26 and hearing loss, it was apparent combined cognitive and hearing status did not have an impact on postural control. Upon examination of the dual-task postural costs, all three groups demonstrated positive costs, yet no group differences existed. However, it appeared that the OAHL group showed reductions in their medial-lateral sway from normal vision to low vision conditions. This suggested that the addition of a low vision challenge threatened balance, resulting in more attentional resources being allocated to reducing postural sway. Unlike postural dual-task costs, there were significant group differences in cognitive dual-task costs under normal vision conditions only. In the normal and low vision conditions, the OAHL group showed no costs, whereas the OANH group demonstrated positive costs (deterioration). Finally, the YA group went from displaying cognitive facilitation in normal vision, to 0 cognitive costs in the low vision condition.

Additional Individual Differences

Exploratory correlations were computed to examine the relationship between the experimental variables and other participant characteristics, such as vision status, balance confidence, and health factors. Dual-task postural and cognitive costs were not correlated, suggesting no evidence of an attentional trade-off between performance domains. However, dual-task cognitive costs in the normal vision condition were positively correlated with cognitive costs in the low vision condition, suggesting an increase in cognitive costs from normal vision to low vision conditions $r(59)=.363$, $p = .005$.

As would be expected, age was positively correlated with decibels of hearing loss, $r(59) = .697$, $p < .0001$. A negative correlation between age and visual acuity $r(59)= -.599$, MoCA scores, $r(27) = .-428$, $p = .026$, and age and Activities-specific Balance Confidence (ABC) scores, $r(59) = -.428$, $p = .005$, were also evident and not unexpected. Hearing loss was also positively associated with gender, $r(59) = .258$, $p = .05$, in that severity of hearing loss is greater for men than women. Visual acuity was negatively correlated with hearing acuity (PTA) such that as hearing loss increased so does vision loss, $r(59) = -4.77$, $p < .001$.

Balance confidence (ABC) scores were negatively associated with using an assistive device, $r(59)= -.469$, $p = .0001$, being previously injured from a fall, $r(59) = -.456$, $p = .001$, and having a fracture below the waist, $r(59) = -.458$, $p < .0001$, indicating that in the present sample, that balance confidence was lower for participants who reported poor mobility or past falls.

Discussion

The primary aim of this study was to use a cognitive-motor dual-task paradigm (Woollacott, 2000) to examine the attentional demands needed to regulate cognitive and postural control performances in younger adults, and older adults with and without hearing loss. Further, we examined the role hearing loss and suggestive mild cognitive impairment play in impacting postural control.

Based on our findings we observed a main effect of task complexity in all four balance parameters examined, indicating that postural control declined as task complexity increased. Increases in instability were evident across the five balance task complexity conditions when using the normal vision single-task balance as a reference point. That is, with the addition of a cognitive load (i.e., dual-task), low vision challenge, cognitive load and low vision challenge, and removal of visual input, total path length, total path velocity and anterior-posterior amplitude increased, therefore indicating increased instability. Yet, using the same reference points, medial-lateral amplitude only significantly increased under three of the four complexity conditions. The single-task low vision challenge did not lead to significant increases in medial-lateral sway, possibly because the visual challenge alone was not attentionally demanding enough and participants had enough cognitive resources to compensate for this visual challenge. Our findings that increased task complexity reduced postural control supports the findings of previous work with younger and older adults who also used a backwards counting tasks (i.e., serial 3s: Condron and Keith, 2002; Jamet et al., 2004, Pellecchia, 2003). Similarly, our results align with Rodriguez et al. (2020) who found that older women aged 60 and over showed significant differences in centre of pressure displacements in anterior-posterior and medial-lateral sway between dual-task versus single-task conditions which also incorporated a serial 7s task. In contrast, we did not find evidence that the addition of a cognitive load improved postural control like researchers such as Riley et al. in 2003 and 2005. One reason for the absence of increased postural performance may be that participants were required to verbally articulate their answers during the serial 7s task. Articulation has been shown to increase postural sway as compared to no articulation (Dault et al., 2003; Yardley et al., 1999) thus becoming another factor which can help explain the presently observed interference in postural control.

Aside from increased cognitive load, the low vision challenge itself also resulted in increases in total path length, path velocity and anterior-posterior amplitude, but not medial-lateral amplitude. These results can be interpreted using the “functional sensitivity hypothesis” which suggests peripheral vision is predominant in controlling antero-posterior sway, whereas central vision predominates medio-lateral control (Agonstoni et al., 2016). As such, participants stared at a fixation point within their zone of central vision. Although the low vision goggles displayed poor visual acuity, participants stood close enough to the fixation point that they could still make use of their central vision. Therefore, it is likely that participants were unable to use their peripheral vision to maintain postural control, and consequently displayed increases in anterior-posterior sway, while medio-lateral sway did not increase as they were able to utilize their central vision. Together our results suggest compensating for vision loss, and/or dividing attention between a balance and a cognitive task, resulted in increased postural instability.

Our second hypothesis examined group differences in postural control. We identified significant interactions of group and balance complexity across the four balance parameters. The interaction appeared to be driven by age when comparing the YAs to the OANH group. That is, the YAs had better postural performance than the OANH group across all balance parameters. These findings are consistent with much of the literature on age-related differences in postural control which shows that postural control worsens with age (Choy et al., 2003; Era et al., 2006; Roman-Liu, 2018). Potential reasons for these age differences can be linked to age-related changes in the musculoskeletal system, such as reduced muscle mass and strength as a result of increasing age (Nolan et al., 2010; Trombetti et al., 2016). Variations in attentional allocation have also been used to explain such age-related differences, as older adults require more attention for postural control and yet have fewer cognitive resources due to aging compared to younger adults, and therefore show larger decrements in postural control (Woollacott & Shumway-Cook, 2002).

Aside from attentional demands, the type of the secondary cognitive task and low vision challenge likely influenced the gap between younger and older adults. As mentioned in the literature, it may be that internal visualization of the mental arithmetic task results in postural decrements. As shown in Figures 2A-2D, the magnitude of the postural instability was significantly larger in older adults than younger adults. Being that older adults depend on visual stimuli more than younger adults for executing cognitive tasks, the serial 7s task may have taxed their visual system, resulting in increased instability compared to younger adults (Jamet et al., 2004). Under the single-task low vision and eyes closed conditions alone, magnitudes of postural control measures were significantly higher among the OANH group compared to the YA group. These age-related differences can be explained by older adults relying more heavily on the visual system to maintain postural control (Choy et al., 2003). Therefore, by adding a low vision challenge or removing a sensory modality (i.e., eyes closed), older adults were no longer able to depend on their visual system, resulting in increased instability. Within the YA group, postural control did not appear to be affected by the addition of a sensory and/or cognitive load, like it was within the OANH group.

Given that older adults demonstrate increased cognitive resource sharing, and sensory loads from hearing loss demand similar resources as postural stability, there are fewer attentional resources available for postural control (Doumas et al., 2008; Li & Lindenberger, 2002). We, therefore expected the interaction between group and task complexity to be driven by hearing status. However, there were no significant group differences in postural control parameters between the OANH and OAHL groups across the five balance complexity conditions except for medial-lateral amplitude in normal and low vision single-task conditions. The differences between the single-task balance conditions but not the dual-task or eyes closed conditions, may be explained by age and compensation. As such, medial-lateral stability has shown to decline with age (Choy et al., 2003), and those within the OAHL group are on average 5.86 years older than those in the OANH group. Medial-lateral sway is controlled by hip abductor-adductor muscle torque, and aging impairs this torque as gluteal hip muscles are susceptible to reductions in muscle fiber quality, and hip abductor strength (Inacio et al., 2019; Ko et al., 2010). Under single-task normal conditions, participants directed their attention to the highly automatized process of balancing which has been shown to increase instability (Huxhold et al., 2006; Wulf et al., 2004). Therefore, under the single-task normal vision condition, we got a true sense of the participants baseline medial-lateral control, which was poorer among the OAHL group compared the OANH group, suggesting changes in the musculoskeletal system may have played a role. Under the single-task low vision condition, the visual challenge appears to have taxed the OAHL groups visual system more than that of the OANH group, therefore these older adults had a harder time compensating for both vision and hearing loss, resulting in increased medial-lateral instability. However, under dual-task conditions, the cognitive task provided an external focus of attention which impacted both the OAHL and OANH group similarly. The lack of group differences in the other balance parameters may be due to the distribution of the hearing loss sample where only five of 16 individuals had moderate hearing loss (41–60 dB HL), and the other 11 have mild hearing loss (26-40 dB HL). Potentially recruiting more older adults with a greater degree of hearing loss, as well as having a more even distribution among hearing loss categories would have allowed for the discovery of an effect of hearing status on postural control.

Considering the association between hearing loss and cognitive decline, we expected to find group differences in postural control between the OANH group and older adults with combined hearing loss and suggestive MCI scores (< 26). We did not find any group differences however, and this may be because we had too large of range in baseline MoCA scores (15-25). Given that the majority of the OAHL group had mild hearing loss, auditory signals may not yet have degraded to the extent where there is an increase in cognitive resources needed for auditory processing. Additionally, it is unknown how long participants have been experiencing hearing loss, therefore it is too early to notice declines in cognitive functioning as suggested by the "sensory deprivation" hypothesis (Dawes et al., 2015). Therefore, we concluded, that postural control was not affected by combined cognitive and hearing status in this sample of older adults.

Another aim of our study was to examine group differences in postural dual-task costs. We found that all three groups displayed postural dual-task costs, however contrary to our hypothesis no group differences were evident in the magnitude of total path length, path velocity, medial-lateral and anterior posterior amplitude, suggesting that the addition of a secondary cognitive task affected all groups' postural control in a similar way. These findings are similar to that of Condron and Keith (2002) who demonstrated no age-related differences in stability under stable platform conditions. Although not significantly different from the older adult groups, younger adults demonstrated the largest costs in total path velocity and anterior-posterior amplitude. Noteworthy, is that baseline postural control scores were miniscule for younger, compared to older adults: that is, even though younger adults displayed larger costs, the magnitude of their postural control was still much lower (i.e., better control) than that of the older adults. Refer to Figures 2A-2D. Increases in postural instability as a result of a backwards counting task has been demonstrated by Pellecchia (2003) and Condron and Keith (2002) among younger adult samples. Yet, our findings also contradict the literature which states the addition of a secondary cognitive task often leads to higher costs in older adults than younger adults, as older adults have limited cognitive resource capacity impacting divided attention during a dual-task (Anderson et al., 2002; Doumas et al., 2009; Woollacoot & Shumway-Cook, 2002). Taking the U-shaped relationship between postural control and cognitive demand (Lacour et al., 2008) into account, we can infer that our secondary cognitive task (i.e., Serial 7s) was demanding enough to tax the cognitive system in both younger and older adults which resulted in attentional resource competition between cognitive and sensorimotor processes disrupting postural control.

When considering the impact of hearing loss on dual-task costs we noticed that the OAHL group displayed significant reductions in total path length and medial-lateral amplitude from normal to low vision conditions, suggesting a difference in attentional allocation because of a visual challenge. These reductions also suggest that the low vision challenge threatened postural control, therefore resulting in an attempt to preserve balance, and reduce falls risk.

Prior to examining cognitive-dual task costs, there were no significant differences in baseline single-task cognitive performance scores between the three groups, therefore all groups performed equally well on the serial 7s task. However, there were significant differences in cognitive dual-task costs between the three groups under the normal vision condition, but this effect disappeared under the low vision condition. The OAHL group demonstrated no cognitive costs in the low and normal vision conditions, that is there was no difference in the number of correct serial 7 subtractions from single to dual-tasks. The YA group displayed cognitive facilitation in the normal vision task, that is they prioritized the cognitive task over the postural task. However, this effect disappeared during the low vision task, as they displayed no costs. However, the OANH group showed positive costs, that is worsened performance from single- to dual-task in both normal and low vision conditions. Potential reasons for cognitive facilitation and no costs may be that since the Wii Balance Board is stationary it does not pose a threat to balance, the YA and OAHL groups felt they could prioritize cognition without compromising postural control. However, this does not explain why the OANH group displayed positive costs. To explain the difference between the older adult groups, we suggest ageism may play a role. As such, the mean age of the OAHL group was 5.86 years older than in the OANH group, therefore, it may be that OAHL group felt as if they had more to prove cognitively, due to their increasing age and did not want to fall into the stereotype that because they are older, they are less competent (Bugental & Hehman, 2007). Regardless of the reasoning, prioritizing cognition over balance is an ineffective dual-task strategy as more attentional resources are being directed toward cognition leaving fewer resources for postural control. This has been termed the posture-second strategy and this pattern is considered maladaptive and may lead to an increased risk of falling. This strategy is often observed in patients with Parkinson's disease, who optimise the cognitive task at the expense of maintaining safe gait and stability (Bloem et al., 2006).

Under the low vision condition, there were no significant group differences in cognitive dual-task costs. However, it was apparent that the addition of a visual load impacted cognitive performance. For example, the OAHL group displayed no costs in both vision conditions. Within the YA group significant differences in costs from normal to low vision were apparent, as they went from displaying negative costs (-27.83%) to no costs. As predicted, the OANH group showed positive costs in both conditions, and although costs increased from 22.99% to 36.58% from normal to low vision conditions respectively, the difference was not significant. Taken together, it appears the addition of a low visual challenge strained the visual system of the YAs but more so for the OANH group, leading to increased cognitive effort for trying to compensate for vision loss, which left fewer resources available for the arithmetic task, resulting in poorer cognitive performance in the low vision condition.

Finally, correlational results revealed that decibels of hearing loss, visual acuity, and global cognitive functioning all worsened with increasing age, which aligns with much of the literature (Feldman & Jacova, 2005; Goman & Lin, 2016; Haegerstrom-Portnoy et al., 1999). We also noted males had higher severity of hearing loss compared to women which as indicated in the literature may be linked to greater occupational noise exposure (Helzner et al., 2005; Mościcki et al., 1985). Balance confidence also declined with increasing age which is supported by the literature (Talley et al., 2008). Other notable factors associated with poor balance confidence were experiencing a previous fall and having a fracture below the waist. Given that lower Activities-specific Balance Confidence scores predict future falls in community dwelling older adults, it is increasingly important that older adults practice safe mobility (Cleary & Skornyakov, 2017). Interestingly, using an assistive device was also associated with reduced balance confidence, which was unexpected as research has shown that using an assistive device is a simple intervention used to improve mobility and balance confidence (Bradley & Hernandez, 2011). However, it is often the case where users experience difficulties with the device, increasing falls risk via tripping, and competition for attentional resources (Bateni & Maki, 2005;

Wright & Kemp, 1992). In summary, it appears balance confidence is poorer among those reporting poor mobility and falls history. The negative correlation between hearing acuity and vision loss indicated that as hearing loss increased visual acuity worsened. Researchers suggest this relationship is a result of hearing and vision loss both being markers of aging, which share common risk factors in addition to age (i.e., stress, lifestyle factors, environmental factors, smoking etc.) (Chia et al., 2006). Collectively, aging is associated with declines in sensory and cognitive functioning, as well as balance confidence, therefore demonstrating the need to attend to sensory and balance impairments to enhance quality of life and safe mobility.

Limitations and Future Directions

There were several limitations in this study that need to be addressed to improve future research projects. Considering the absence of group differences in postural dual-task costs, it was likely due to the balance task itself (i.e., quiet stance on a firm surface) not being challenging enough to pose a threat to postural control. As such, we did not see changes in postural dual-task costs from normal to low vision which we had originally anticipated. To address the difficulty of the postural control task, incorporating a more threatening postural task would likely yield age differences in dual-task costs, and support for the *Posture First Principle*. Many studies use tilting platforms to threaten postural control, which must be used in traditional lab settings with safety (e.g., harnesses) and special equipment. We, however, chose to collect data outside the lab in a highly trafficked public area (i.e., mall), at the expense of not posing a threat to balance. This allowed us to collect data from a more diverse sample of older adults. It is important to note, that our study like many others, do not necessarily reflect balancing in everyday situations. For example, standing in a grocery aisle to reach a can of soup is much different than standing on a stationary board, as it incorporates movement of arms, visual scanning, listening to the intercom, being aware of one's surroundings, etc. Future experiments should focus on mimicking daily life encounters, to truly understand how balance is compromised.

To understand the role of dual-task prioritization, future studies might additionally ask participants which task they felt that they were prioritizing (i.e., cognitive vs. balance). It would be interesting to see if the subjective responses correlate with objective postural control data, as it would help us better understand how direction of prioritization impacts dual-task performance. It also would have been beneficial to include a self-report questionnaire to evaluate whether or not older adults fear conforming to age stereotypes, especially in tasks that involve verbal answers. This would further help to address whether age-related stereotypes of cognitive decline are influential on participants' degree of motivation toward performing the cognitive task well. Furthermore, we did not consider how much cognitive and postural effort participants were putting into the cognitive and/or postural control tasks. In future, researchers should incorporate some form of subjective effort scale, as this might elucidate further the direction of attentional allocation during dual-task conditions.

Notably, we did not stratify across levels of hearing loss severity. As mentioned earlier, our hearing loss sample consisted of an uneven distribution of individuals with either mild or moderate hearing impairment, and no individuals with severe or profound hearing impairments. This was likely why we did not find strong effects of hearing status on postural control. Future research should recruit and compare different levels of hearing loss to examine the effect of hearing loss severity on balance performance, taking into consideration those who utilize hearing aids.

Lastly, although under simulated low vision conditions, participants with hearing loss are somewhat comparable to individuals with dual-sensory loss, we did not consider how postural control would be impacted by individuals with actual vision loss or with dual-sensory loss. Additionally, although the visual acuity scores among our older adult groups did display minimal vision loss, we did not consider them to have dual-sensory loss. Further, some of the visual acuity scores did not represent participants' true vision, as ten older adult participants forgot to bring their glasses, thus reflecting uncorrected visual acuity scores. Future studies would benefit from recruiting those with no sensory loss, hearing loss, vision loss, and dual-sensory loss to examine how progressive and chronic sensory impairments affect balance performance independently and in conjunction.

Conclusion

In summary, we used a dual-task paradigm to examine differences in attentional resource allocation as task complexity increased. Our results add a new understanding to how postural control can be impacted by combined cognitive load and a visual challenge. More specifically, we demonstrated that increased cognitive and visual loads impact postural control differently when comparing younger and older adults. Across five balance conditions with increased task complexity (visual and/or cognitive challenge) older adults with and without hearing loss had significantly worse postural control compared to younger adults. These age-related declines in balance performance are likely due to musculoskeletal declines, reduced cognitive resources, and difficulty dividing attention. Older adults with and without hearing loss did not differ in postural control, except for medial-lateral amplitude. Considering the age differences between these groups suggests the decline in medial-lateral amplitude is more pronounced with increasing age and compensating for low vision is more challenging for those with hearing loss. We further demonstrated that no group differences occurred in postural dual-task costs, which was likely due to the balance task not posing a postural threat. However, among those with hearing loss the presence of a low vision challenge posed a threat to balance resulting in allocating more cognitive resources towards preserving medial-lateral amplitude, reducing total path length. Interestingly, older adults with hearing loss demonstrated no costs in both normal and low vision tasks, whereas older adults without hearing loss displayed maladaptive performances. We suggested that age differences in motivation to perform well cognitively may play a role. Finally, we saw no differences in postural performance between older adults with combined hearing loss and MoCA scores below the 26 cut off (i.e., suggestive of MCI) and older adults with no such impairments, which is likely due to the low severity of hearing loss.

Our results are useful when trying to understand the interconnections between sensory loss, increased cognitive load and postural control across different age groups. As previously mentioned, the prevalence rates of hearing, vision loss, and cognitive decline are likely to increase given the world population aged 60 years and older is expected to reach 2 billion by 2050 (World Health Organization, 2018), meaning falls prevalence is likely to increase as well. Given that sensory losses can increase postural instability (Lin & Ferrucci, 2012; Reed-Jones et al., 2013), it is important for younger adults to be proactive towards their sensory health and for older adults to seek treatment in correcting such impairments if possible, as they can eventually have negative effects on cognitive performance (Uchida et al., 2019). Taken together, understanding the interconnections between sensory, cognitive, and motor functioning is critical in reducing falls, and attempting to preserve healthy aging and mobility.

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Tables

Table 1

Means and standard deviations for demographic and cognitive scores measures by group

Source	OANH	OAHL	YA	*p*
Age	71.23 (11.30)	77.13 (7.56)	23.03 (3.53)	.0001
Percent Female	72.7%	50.0%	78.10%	.137
MoCA (max.30)	24 (3.29)	22.25 (4.04)	N/A	.246
Visual Acuity	.706 (.30)	.598 (.26)	1.19 (.46)	.025
ABC Scale	75.87 (26.30)	79.00 (19.99)	91.89 (7.45)	.005
PTA	19.20 (5.82)	38.20 (9.00)	10.20 (0.56)	.0001
Percent with Falls History	72.7%	75.0%	46.9%	.108
Percent Injured from Fall	36.4%	37.5%	28.1%	.774
Percent with Previous Fracture Below Waist	18.2%	25.0%	18.8%	.869
Percent Using Assistive Device	18.2%	18.8%	0%	.039
Number of Correct S7s Single-Task	6.46 (3.75)	7.37 (3.75)	6.03 (4.90)	.613
Number of Correct S7s Dual-Task (NV)	5.27 (3.88)	8.25 (4.68)	7.19 (5.11)	.291
Number of Correct S7s Dual-Task (LV)	4.00 (2.53)	7.38 (4.06)	6.28 (4.66)	.127

Note. OANH = Older adults with normal hearing, OAHL = Older adults with hearing loss, YA = Younger adults, MoCA = Montreal Cognitive Assessment, ABC = Activities-specific Balance Confidence Scale, PTA = Pure Tone Average.

Table 2A

Analysis of Variance for Total Path Length Across Task Complexity

Source	SS	df	MS	F	p	η_p^2
Task Complexity	4438236.647	1.92	2311599.83	21.539	<.0001	.278
Task Complexity * Group	2113397.225	3.84	550368.204	5.128	.001	.155
Error	11539019.84	107.519	107320.6			

Table 2B

Analysis of Variance for Medial-lateral Amplitude Across Task Complexity

Source	SS	df	MS	F	p	η_p^2
Task Complexity	7326.708	2.115	3464.556	11.702	.0001	.173
Task Complexity * Group	6944.057	4.23	1641.806	5.546	<.0001	.165
Error	35060.884	118.427	296.056			

Table 2C

Analysis of Variance for Anterior-Posterior Amplitude Across Task Complexity

Source	SS	df	MS	F	p	η_p^2
Task Complexity	22757.932	2.663	8547.541	29.323	.001	.344
Task Complexity * Group	11130.15	5.325	2090.16	7.17	<.0001	.204
Error	43462.339	149.101	291.497			

Table 2D

Analysis of Variance for Total Path Velocity Across Task Complexity

Source	SS	df	MS	F	Sig.	η_p^2
Task Complexity	4937.928	1.919	2572.667	21.547	<.0001	.278
Task Complexity * Group	2351.276	3.839	612.509	5.13	.001	.155
Error	12833.559	107.485	119.398		.001	

Table 3A

*Between subjects one-way ANOVA: Age * Task complexity (Total Path Length) (OANH vs. YA)*

Measure		Sum of Squares	df	Mean Square	F	*p*
Eyes Closed	Between Groups	13871289.61	1	1E+07	225.09	<.0001
	Within Groups	2526598.558	41	61624		
	Total	16397888.17	42			
LV-Single	Between Groups	8019263.119	1	8E+06	205.77	<.0001
	Within Groups	1597867.537	41	38972		
	Total	9617130.656	42			
LV-Dual	Between Groups	12180728.32	1	1E+07	247.74	<.0001
	Within Groups	2015879.288	41	49168		
	Total	14196607.61	42			
NV-Single	Between Groups	6713253.238	1	7E+06	297.76	<.0001
	Within Groups	924369.424	41	22546		
	Total	7637622.662	42			
NV-Dual	Between Groups	11196866.22	1	1E+07	160.81	<.0001
	Within Groups	2854835.887	41	69630		
	Total	14051702.11	42			

Note. LV-Single = Low Vision Single-Task, LV-Dual = Low Vision Dual-Task, NV-Single = Normal Vision Single-Task, NV-Dual = Normal Vision Dual-Task

Table 3B

*Between subjects one-way ANOVA: Age * Task complexity (Medial-Lateral Amplitude) (OANH vs. YA)*

Measure		Sum of Squares	df	Mean Square	F	*p*
Eyes Closed	Between Groups	15413.452	1	15413	52.003	<.0001
	Within Groups	12152.176	41	296.4		
	Total	27565.628	42			
LV-Single	Between Groups	2604.303	1	2604.3	209.16	<.0001
	Within Groups	510.495	41	12.451		
	Total	3114.799	42			

LV-Dual	Between Groups	7445.634	1	7445.6	142.51	<.0001
	Within Groups	2142.048	41	52.245		
	Total	9587.682	42			
NV-Single	Between Groups	2025.581	1	2025.6	93.991	<.0001
	Within Groups	883.584	41	21.551		
	Total	2909.165	42			
NV-Dual	Between Groups	7810.57	1	7810.6	98.681	<.0001
	Within Groups	3245.133	41	79.15		
	Total	11055.702	42			

Note. LV-Single = Low Vision Single-Task, LV-Dual = Low Vision Dual-Task, NV-Single = Normal Vision Single-Task, NV-Dual = Normal Vision Dual-Task

Table 3C

*Between subjects one-way ANOVA: Age * Task complexity (Anterior-Posterior Amplitude) (OANH vs. YA)*

Measure		Sum of Squares	df	Mean Square	F	*p*
Eyes Closed	Between Groups	38276.211	1	38276	86.018	<.0001
	Within Groups	18244.124	41	444.98		
	Total	56520.334	42			
LV-Single	Between Groups	6783.436	1	6783.4	30.181	<.0001
	Within Groups	9215.212	41	224.76		
	Total	15998.648	42			
LV-Dual	Between Groups	7445.634	1	7445.6	142.51	<.0001
	Within Groups	2142.048	41	52.245		
	Total	9587.682	42			
NV-Single	Between Groups	4927.582	1	4927.6	42.275	<.0001
	Within Groups	4778.975	41	116.56		
	Total	9706.557	42			
NV-Dual	Between Groups	8848.834	1	8848.8	52.582	<.0001
	Within Groups	6899.697	41	168.29		
	Total	15748.531	42			

Note. LV-Single = Low Vision Single-Task, LV-Dual = Low Vision Dual-Task, NV-Single = Normal Vision Single-Task, NV-Dual = Normal Vision Dual-Task

Table 3D

*Between subjects one-way ANOVA: Age * Task complexity (Total Path Velocity) (OANH vs. YA)*

Measure		Sum of Squares	df	Mean Square	F	*p*
Eyes Closed	Between Groups	15429.21	1	15429	225.18	<.0001
	Within Groups	2809.345	41	68.521		
	Total	18238.555	42			
LV-Single	Between Groups	8919.204	1	8919.2	205.89	<.0001
	Within Groups	1776.126	41	43.32		
	Total	10695.33	42			
LV-Dual	Between Groups	13544.461	1	13544	247.76	<.0001
	Within Groups	2241.407	41	54.668		
	Total	15785.868	42			
NV-Single	Between Groups	7466.892	1	7466.9	297.97	<.0001
	Within Groups	1027.441	41	25.06		
	Total	8494.333	42			
NV-Dual	Between Groups	12450.008	1	12450	160.84	<.0001
	Within Groups	3173.662	41	77.406		
	Total	15623.67	42			

Note. LV-Single = Low Vision Single-Task, LV-Dual = Low Vision Dual-Task, NV-Single = Normal Vision Single-Task, NV-Dual = Normal Vision Dual-Task

Table 4

*Between subjects one-way ANOVA: Hearing status and older age * Task complexity (OANH vs. OAHL)*

Measure		Sum of Squares	df	Mean Square	F	*p*
LV-Single	Between Groups	714.989	1	714.99	4.648	.041
	Within Groups	3845.937	25	153.84		
	Total	4560.927	26			
NV-Single	Between Groups	614.219	1	614.22	4.607	.042
	Within Groups	3333.262	25	133.33		
	Total	3947.481	26			

Note. LV-Single = Low Vision Single-Task, NV-Single = Normal Vision Single-Task,

Table 5A

Normal Vision Postural Dual-Task Costs

	Normal Vision							
	TPL		MLamp		APamp		TPV	
Group	*M*	*SE*	*M*	*SE*	*M*	*SE*	*M*	*SE*
OANH	26.5153	5.70402	158.648	68.8555	58.4043	21.9522	26.4988	5.70285
OAHL	31.8372	7.57829	143.887	53.3621	47.8086	16.2121	31.8353	7.57527
YA	26.0917	7.13699	88.4415	16.3846	80.7585	22.8354	26.0871	7.13447

Note. OANH = Older adults with normal hearing, OAHL = Older adults with hearing loss, YA = Younger adults, M = mean, SE = standard error, TPL = total path length (mm), MLamp = medial-lateral amplitude (mm), APamp = anterior-posterior amplitude (mm), TPV = total path velocity (mm/s).

Table 5B

Low Vision Postural Dual-Task Costs

	Low Vision							
	TPL		MLamp		APamp		TPV	
Group	*M*	*SE*	*M*	*SE*	*M*	*SE*	*M*	*SE*
OANH	26.5653	7.154	101.811	43.5794	56.8123	24.2865	26.5477	7.14855
OAHL	17.4264	5.18362	51.3886	34.6383	31.5799	11.4969	17.4197	5.18359
YA	32.2513	11.2554	108.658	35.3964	103.793	47.4842	32.2381	11.2548

Note. OANH = Older adults with normal hearing, OAHL = Older adults with hearing loss, YA = Younger adults, M = mean, SE = standard error, TPL = total path length (mm), MLamp = medial-lateral amplitude (mm), APamp = anterior-posterior amplitude (mm), TPV = total path velocity (mm/s).

Table 6

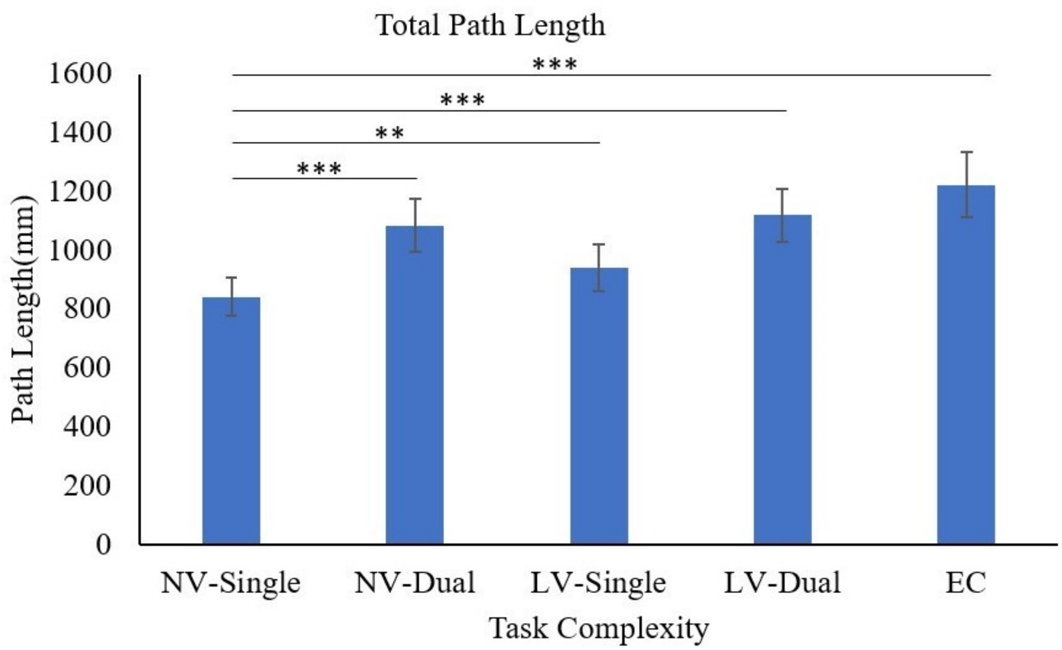
Cognitive Dual-Task Costs

	Normal Vision		Low Vision	
Group	*M*	*SE*	*M*	*SE*
OANH	22.9865	7.3073	36.5845	11.46
OAHL	-42.245	23.0847	-23.20	16.3859
YA	-27.831	8.99475	-24.71	23.15

Note. OANH = Older adults with normal hearing, OAHL = Older adults with hearing loss, YA = Younger adults, M = mean, SE = standard error

Figure 1A

Average Differences in Total Path Length Based on Increasing Task Complexity

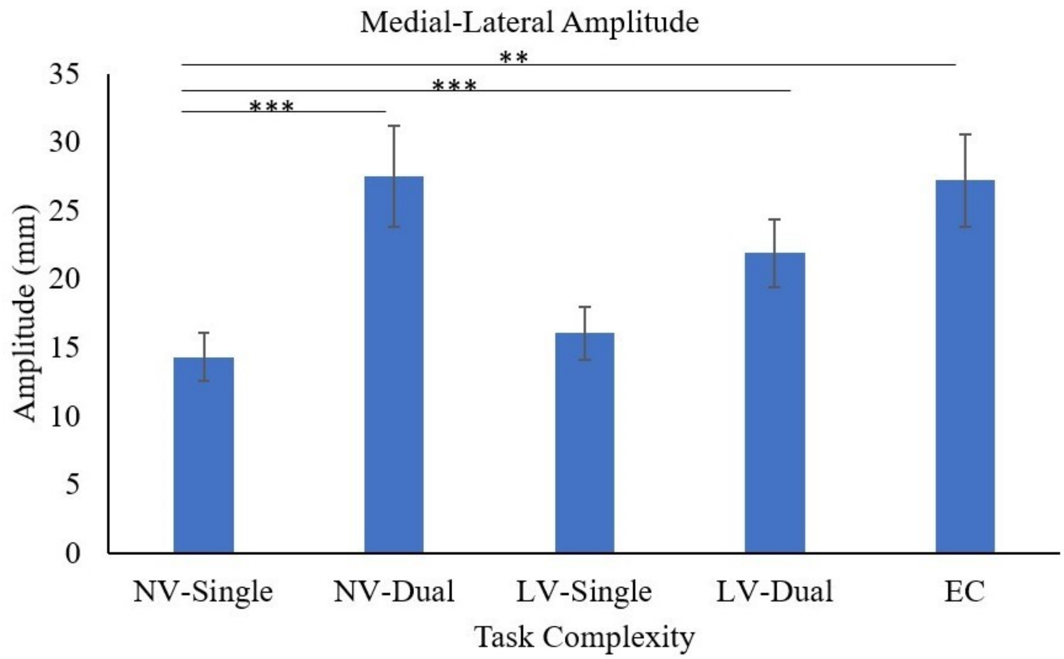


Note. OANH = Older adults with normal hearing, OAHL = Older adults with hearing loss, YA = Younger adults; NV-Single = Normal vision single-task, NV-Dual = Normal vision dual-task, LV-Single = Low vision-single task, LV-Dual = Low vision dual-task, EC = Eyes closed.

This figure presents differences in total path length (mm) across balance task complexity. Higher values indicate greater total sway, or poorer postural control. All conditions statistically differed from that of the normal vision single-task condition. Thus, as the balance task complexity increased, total path length (mm) increased, or balance performance decreased. Error bars show standard error of the mean. ***$p < .0001$, ** $p < .01$

Figure 1B

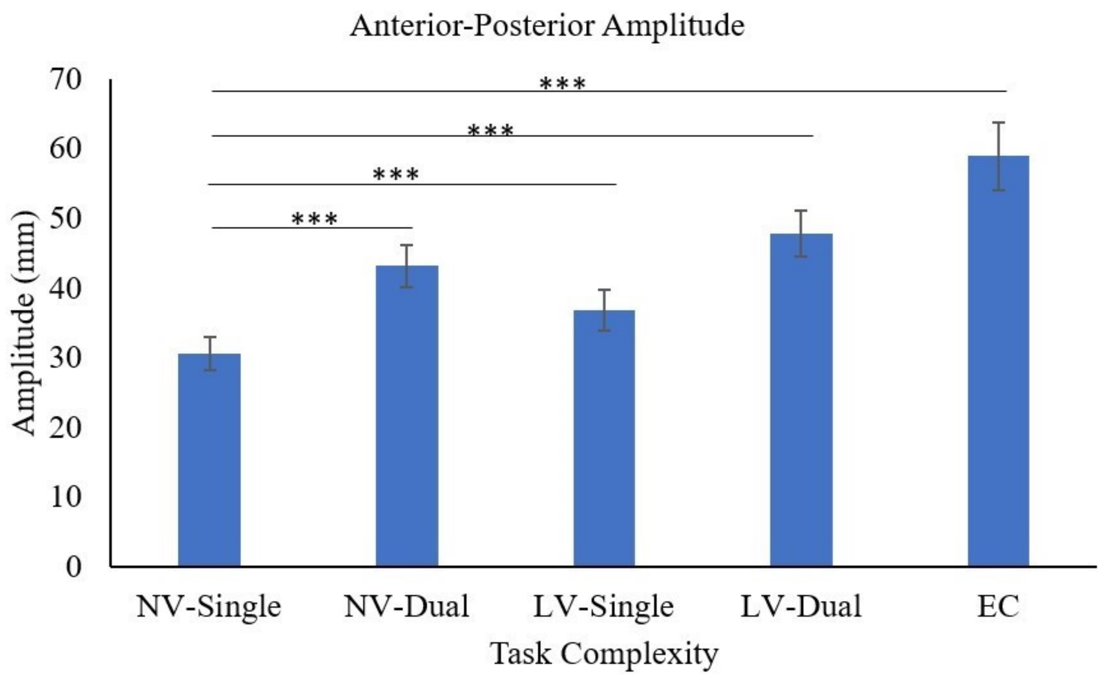
Average Differences in Medial-Lateral Amplitude Based on Increasing Task Complexity



Note. OANH = Older adults with normal hearing, OAHL = Older adults with hearing loss, YA = Younger adults; NV-Single = Normal vision single-task, NV-Dual = Normal vision dual-task, LV-Single = Low vision-single task, LV-Dual = Low vision dual-task, EC = Eyes closed. This figure presents differences in medial-lateral amplitude (mm) across balance task complexity. Higher values indicate greater left-right sway, or poorer postural control. All conditions statistically differed from that of the normal vision single-task condition except the low vision single-task condition. Thus, as the balance task complexity increased, medial-lateral amplitude (mm) increased, or balance performance decreased. Error bars show standard error of the mean. ***$p < .0001$, ** $p < .01$

Figure 1C

Average Differences in Anterior-Posterior Amplitude Based on Increasing Task Complexity

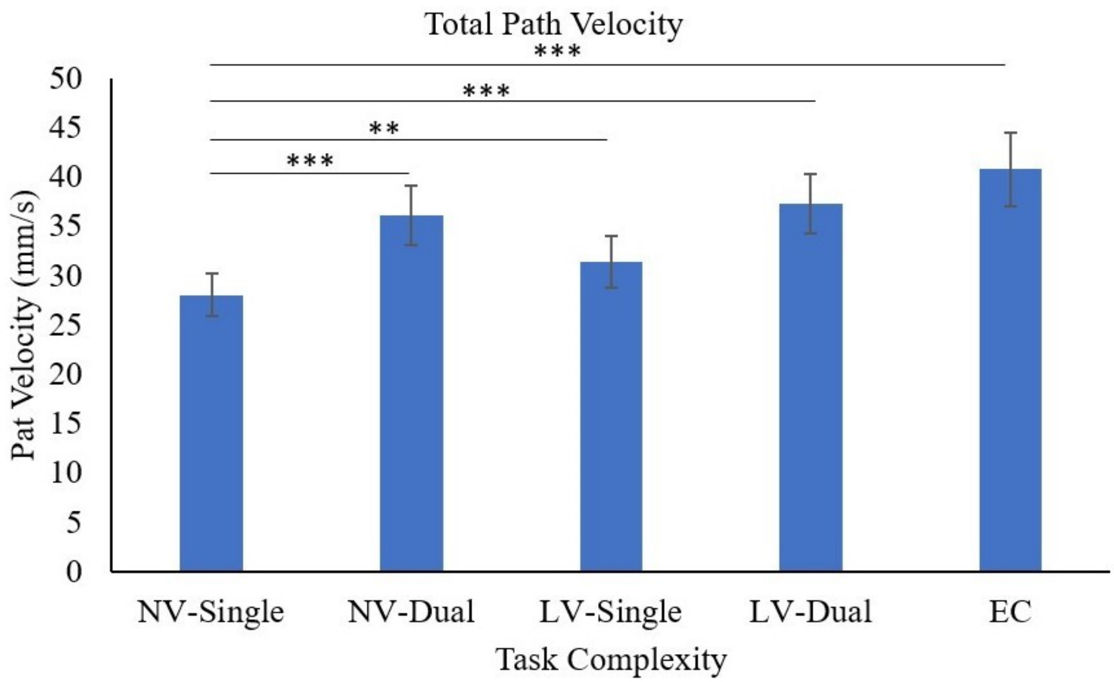


Note. OANH = Older adults with normal hearing, OAHL = Older adults with hearing loss, YA = Younger adults; NV-Single = Normal vision single-task, NV-Dual = Normal vision dual-task, LV-Single = Low vision-single task, LV-Dual = Low vision dual-task, EC = Eyes closed.

This figure presents differences in anterior-posterior amplitude (mm) across balance task complexity. Higher values indicate greater forward-backward sway, or poorer postural control. All conditions statistically differed from that of the normal vision single-task condition. Thus, as the balance task complexity increased, anterior-posterior amplitude increased, or balance performance decreased. Error bars show standard error of the mean. ***$p < .0001$

Figure 1D

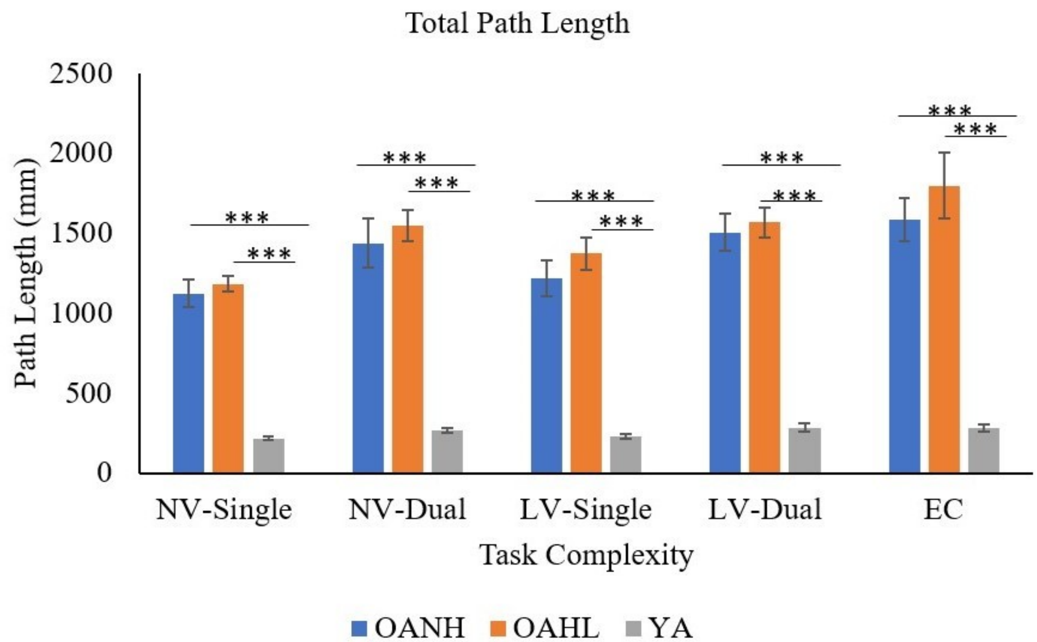
Average Differences in Total Path Velocity Based on Increasing Task Complexity



Note. OANH = Older adults with normal hearing, OAHL = Older adults with hearing loss, YA = Younger adults; NV-Single = Normal vision single-task, NV-Dual = Normal vision dual-task, LV-Single = Low vision-single task, LV-Dual = Low vision dual-task, EC = Eyes closed.
This figure presents differences in total path velocity (mm/s) across balance task complexity. Higher values indicate greater total path velocity, or poorer postural control. All conditions statistically differed from that of the normal vision single-task condition. Thus, as the balance task complexity increased, total path velocity (mm) increased, or balance performance decreased. Error bars show standard error of the mean. ***$p < .0001$, ** $p < .01$

Figure 2A

Group Differences in Average Total Path Length

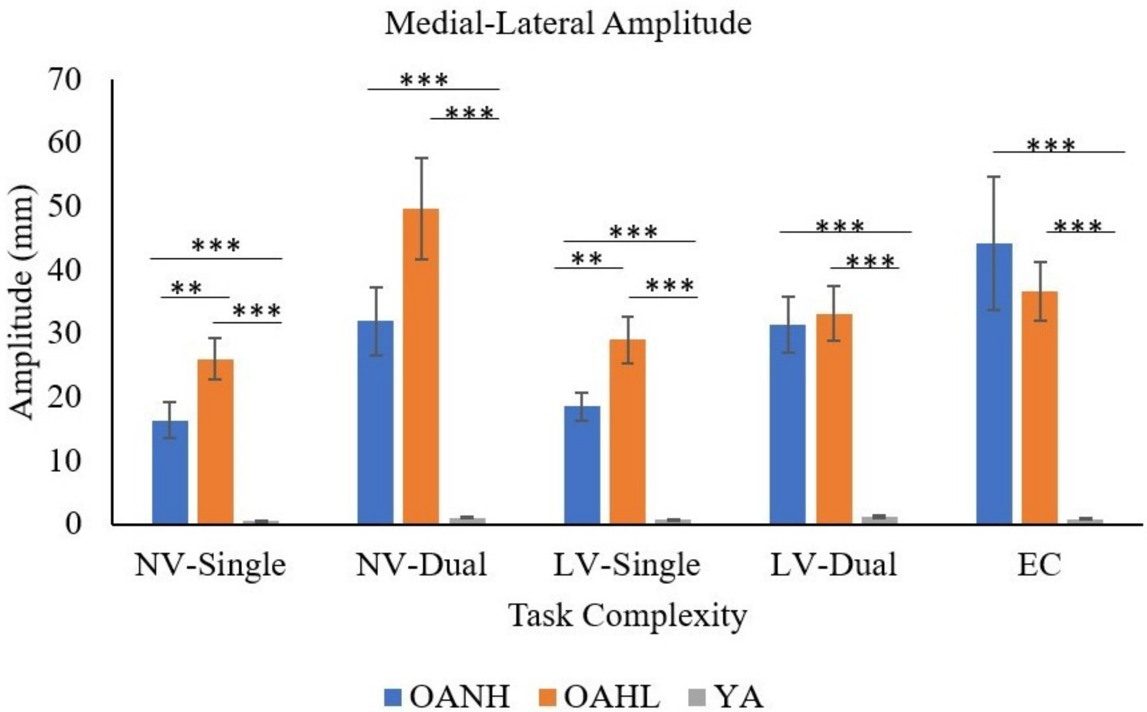


Note. OANH = Older adults with normal hearing, OAHL = Older adults with hearing loss, YA = Younger adults; NV-Single = Normal vision single-task, NV-Dual = Normal vision dual-task, LV-Single = Low vision-single task, LV-Dual = Low vision dual-task, EC = Eyes closed.

This figure depicts group differences in total path length (mm). Significant differences were only evident when comparing the YA to the OANH and OAHL groups. The YA group had better postural control as indicated by a lower magnitude of total path length (mm). ***$p < .0001$

Figure 2B

Group Differences in Average Medial-Lateral Amplitude

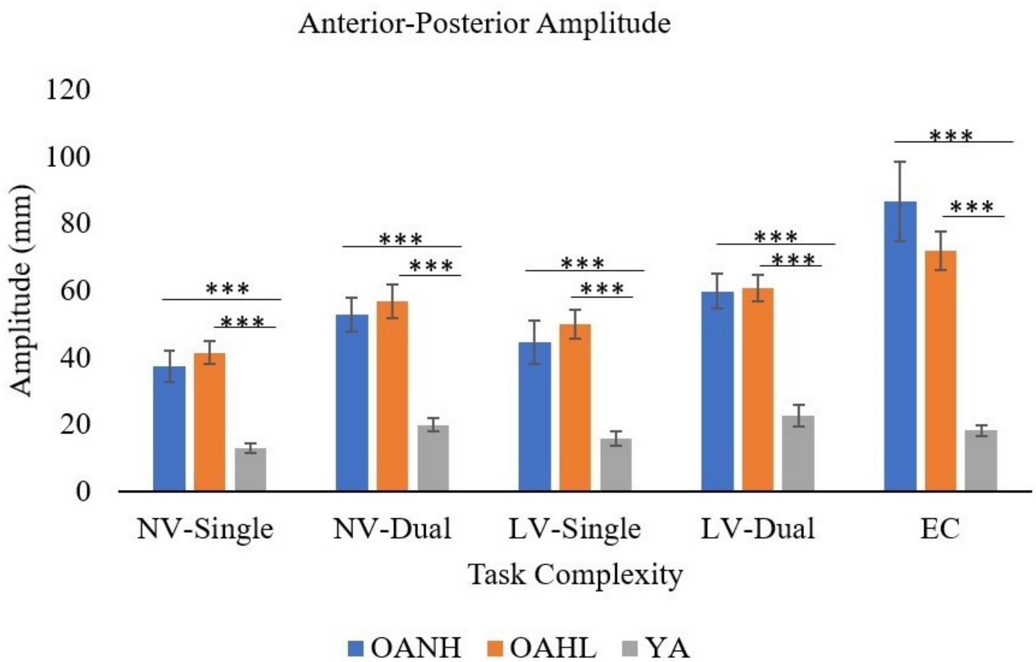


Note. OANH = Older adults with normal hearing, OAHL = Older adults with hearing loss, YA = Younger adults; NV-Single = Normal vision single-task, NV-Dual = Normal vision dual-task, LV-Single = Low vision-single task, LV-Dual = Low vision dual-task, EC = Eyes closed.

This figure depicts group differences in medial-lateral amplitude (mm). Significant differences were evident when comparing the YA to the OANH and OAHL groups. The YA group had better postural control as indicated by a lower magnitude of medial-lateral amplitude (mm). The OANH and OAHL group only showed significant differences in medial-lateral amplitude in the normal vision single- and dual-task and low vision single task. ***$p < .0001$ ** $p < .01$

Figure 2C

Group Differences in Average Anterior-Posterior Amplitude

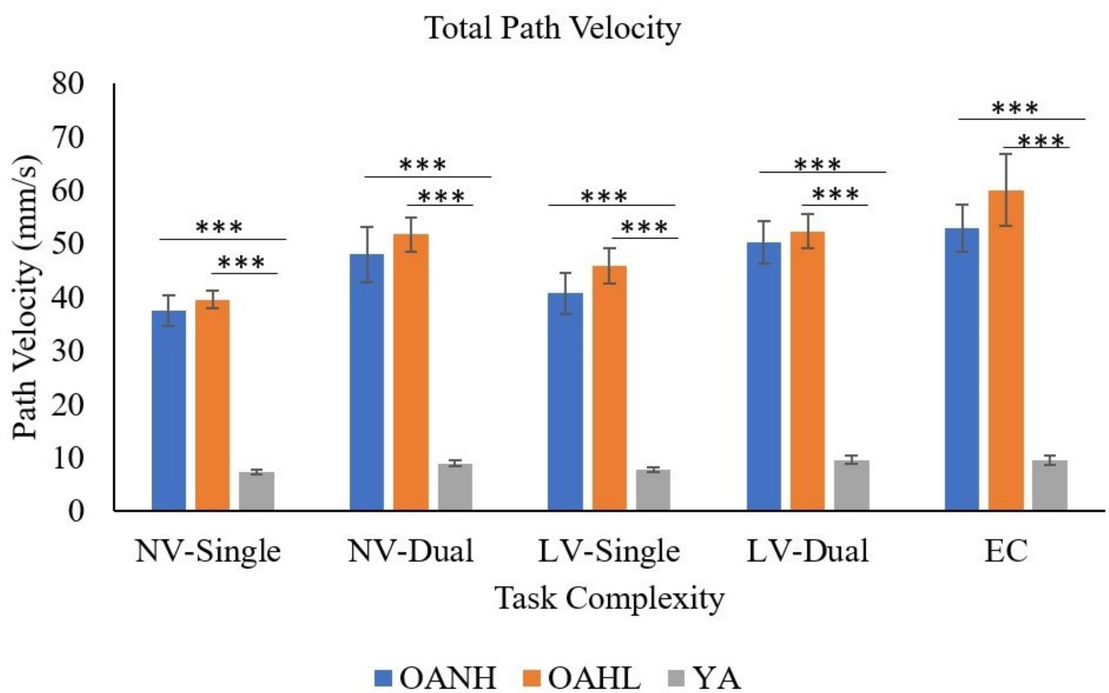


Note. OANH = Older adults with normal hearing, OAHL = Older adults with hearing loss, YA = Younger adults; NV-Single = Normal vision single-task, NV-Dual = Normal vision dual-task, LV-Single = Low vision-single task, LV-Dual = Low vision dual-task, EC = Eyes closed.

This figure depicts group differences in anterior-posterior amplitude (mm). Significant differences were only evident when comparing the YA to the OANH and OAHL groups. The YA group had better postural control as indicated by a lower magnitude of anterior-posterior amplitude (mm). ***$p < .0001$

Figure 2D

Group Differences in Average Total Path Velocity

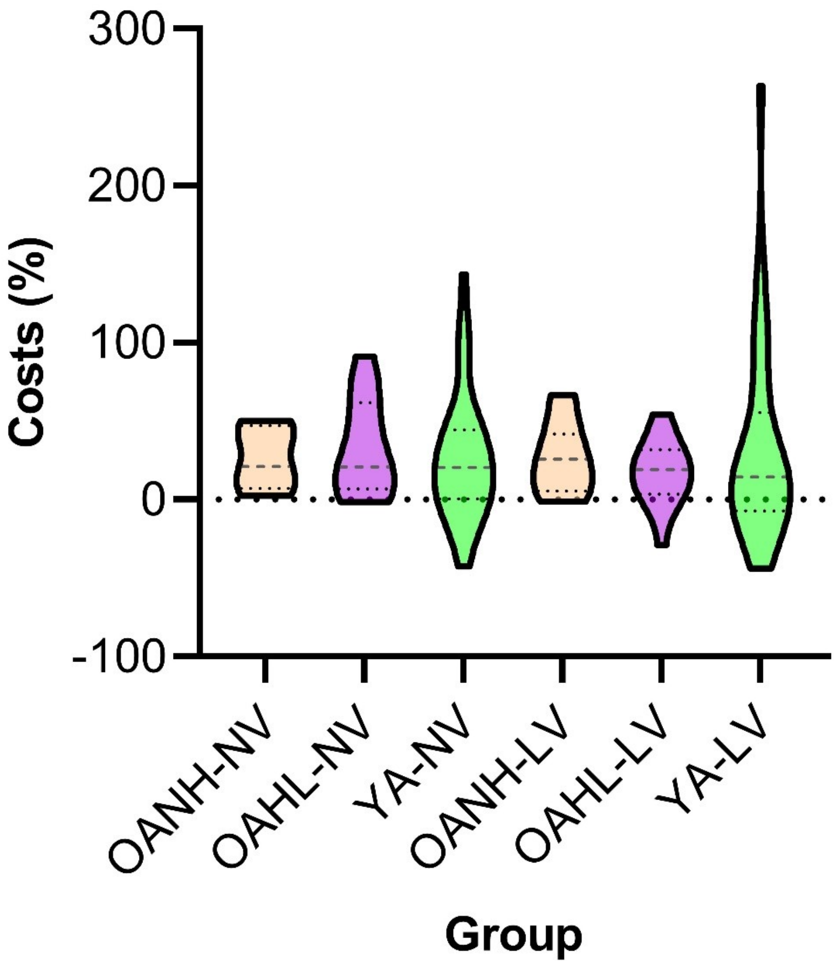


Note. OANH = Older adults with normal hearing, OAHL = Older adults with hearing loss, YA = Younger adults; NV-Single = Normal vision single-task, NV-Dual = Normal vision dual-task, LV-Single = Low vision-single task, LV-Dual = Low vision dual-task, EC = Eyes closed.

This figure depicts group differences in total path velocity (mm/s). Significant differences were only evident when comparing the YA to the OANH and OAHL groups. The YA group had better postural control as indicated by a lower magnitude of total path velocity (mm/s). ***p < .0001

Figure 3A

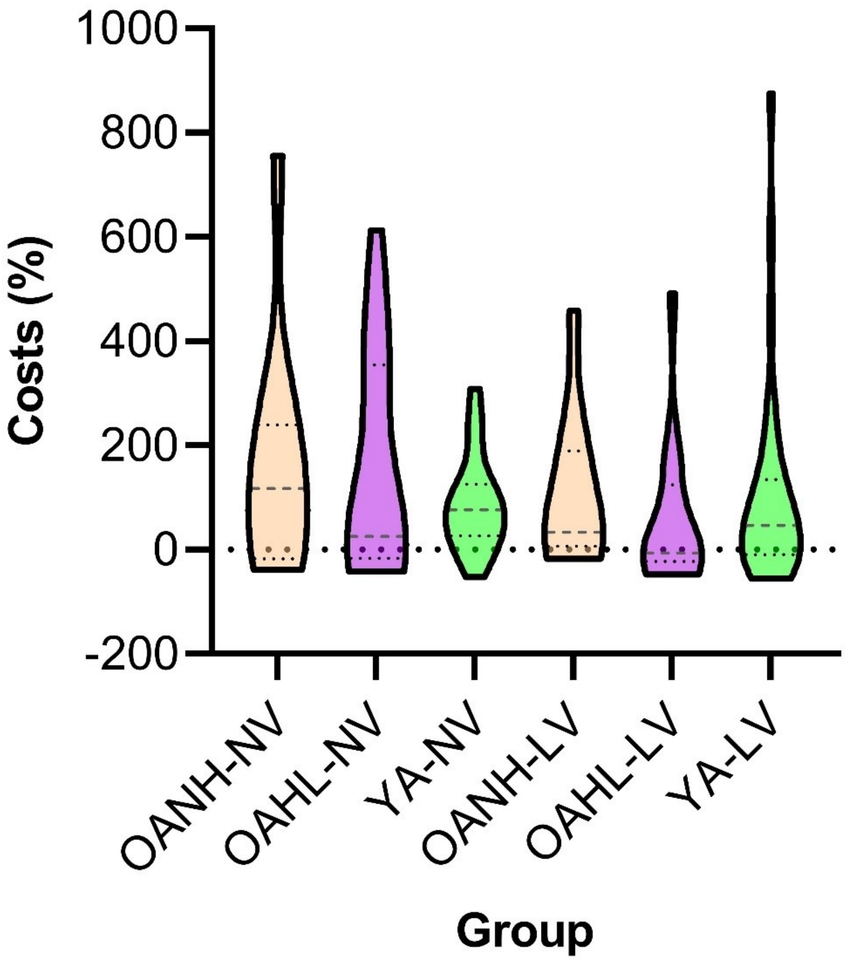
Group Differences Based on Average Total Path Length Dual-Task Costs



Note. OANH = Older adults with normal hearing, OAHL = Older adults with hearing loss, YA = Younger adults; NV = Normal vision, LV = Low vision. This figure depicts the probability density of total path length (mm) based on group and vision condition. Based on averages, all groups displayed positive costs. No significant differences between the groups were found.

Figure 3B

Group Differences Based on Average Medial-Lateral Amplitude Dual-Task Costs

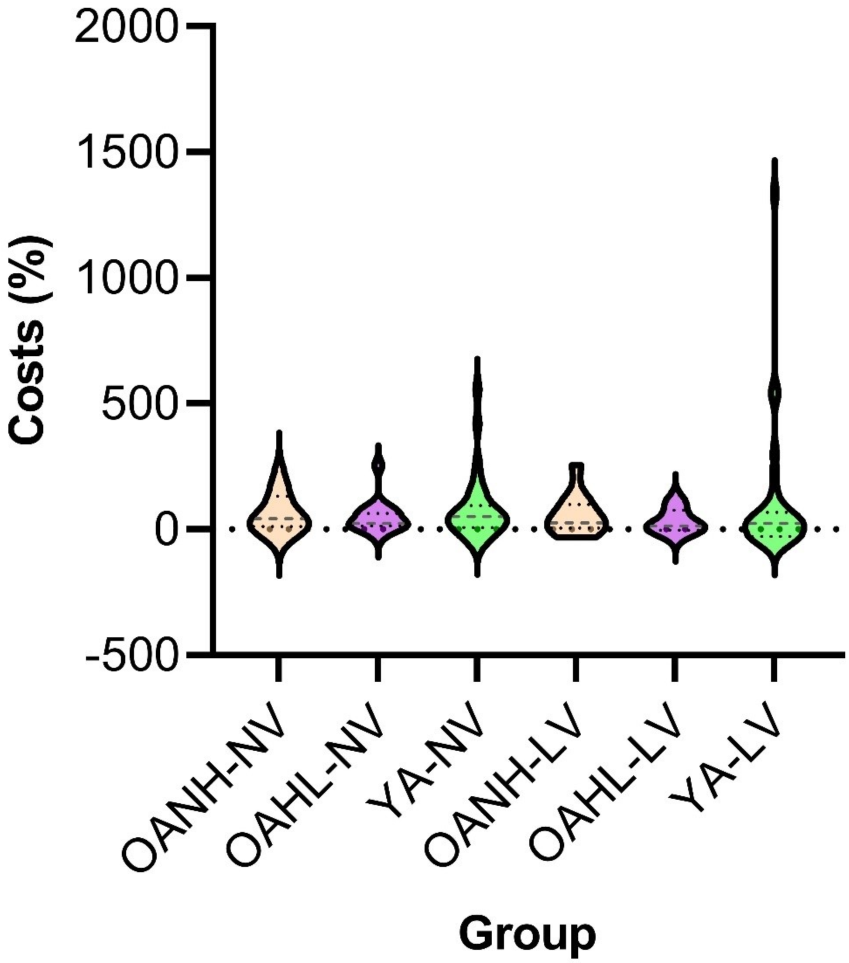


Note. OANH = Older adults with normal hearing, OAHL = Older adults with hearing loss, YA = Younger adults; NV = Normal vision, LV = Low vision

This figure depicts the probability density of medial-lateral amplitude (mm) based on group and vision condition. Based on averages, all groups displayed positive costs. No significant differences between the groups were found.

Figure 3C

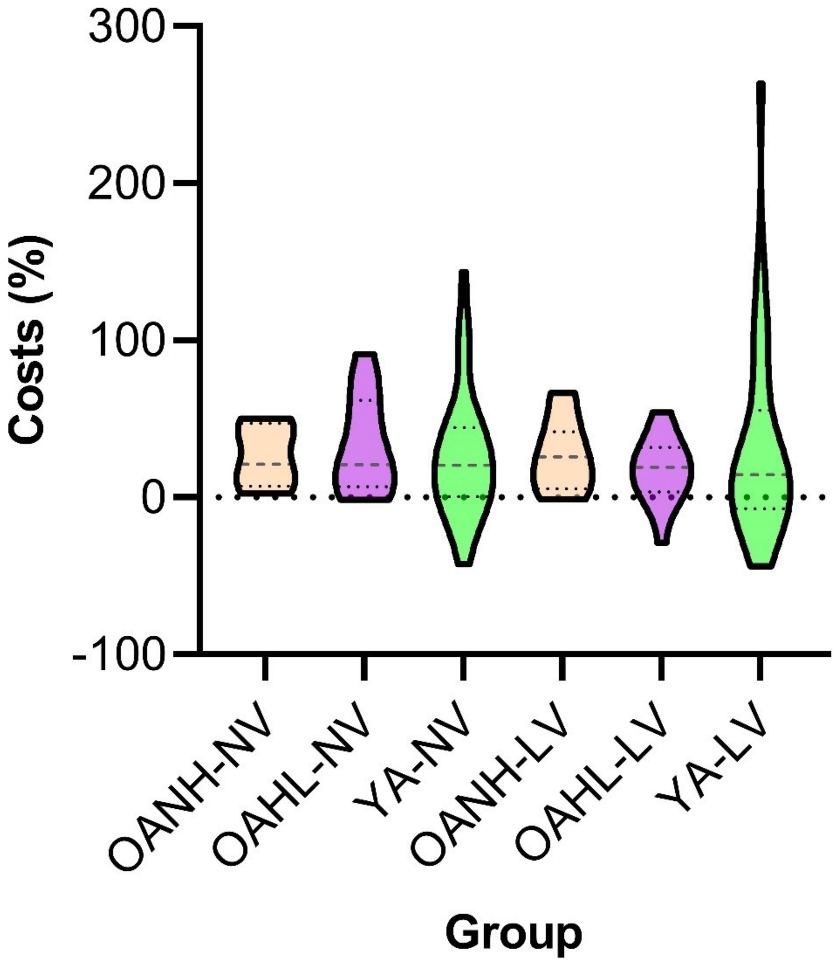
Group Differences Based on Average Anterior-Posterior Amplitude Dual-Task Costs



Note. OANH = Older adults with normal hearing, OAHL = Older adults with hearing loss, YA = Younger adults; NV = Normal vision, LV = Low vision. This figure depicts the probability density of anterior-posterior amplitude (mm) based on group and vision condition. Based on averages, all groups displayed positive costs. No significant differences between the groups were found.

Figure 3D

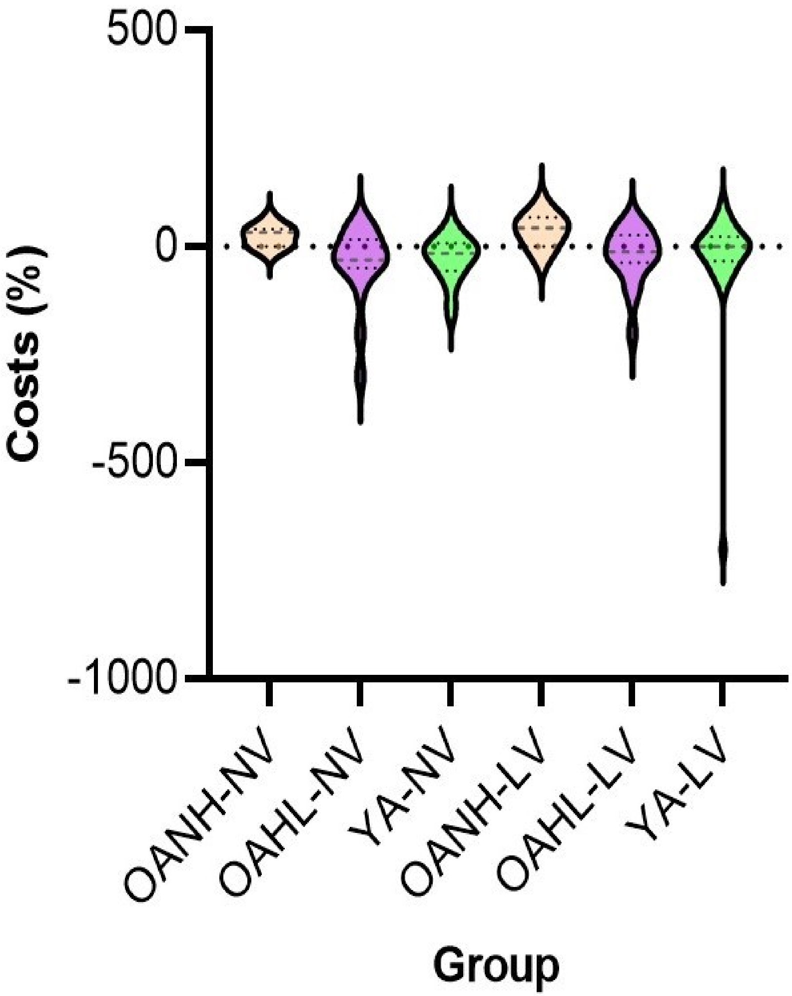
Group Differences Based on Total Path Velocity Dual-Task Costs



Note. OANH = Older adults with normal hearing, OAHL = Older adults with hearing loss, YA = Younger adults; NV = Normal vision, LV = Low vision. This figure depicts the probability density of total path velocity (mm/s) based on group and vision condition. Based on averages, all groups displayed positive costs. No significant ($p < .05$) differences between groups were found.

Figure 4

Group Differences in Average Cognitive Dual-Task Costs



Note. OANH = Older adults with normal hearing, OAHL = Older adults with hearing loss, YA = Younger adults; NV = Normal vision, LV = Low vision. This figure depicts the probability density of cognitive (serial 7s) dual-task costs based on group and vision condition. The OANH group demonstrated positive costs in both normal and low vision conditions. The YA group demonstrated negative costs in the normal vision condition and no costs in the low vision condition. The OAHL group showed no costs in either normal or low vision conditions. Significant (*p* <. 05) group differences between the OAHL and OANH group were apparent under normal vision conditions but not low vision conditions.