Interventions to Improve Cognitive-Motor Dual Tasking in Older Adults: Mechanisms of Training and Effects of Inter-Individual Differences on Training Efficacy

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A Thesis
in the Department
of
Psychology

Presented in Partial Fulfillment of the Requirements
For the Degree of
Doctor of Philosophy (Psychology)
Concordia University
Montreal, Quebec, Canada

May 2025

CONCORDIA UNIVERSITY
SCHOOL OF GRADUATE STUDIES

This is to certify that the thesis prepared

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Entitled: Interventions to Improve Cognitive-Motor Dual Tasking in Older Adults:
Mechanisms of Training and Effects of Inter-Individual Differences on Training Efficacy

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

Doctor Of Philosophy

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Abstract

Interventions to Improve Cognitive-Motor Dual Tasking in Older Adults: Mechanisms of Training and Effects of Inter-Individual Differences on Training Efficacy

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Concordia University, 2025

This dissertation includes three studies that contribute to the cognitive and motor aging literature by exploring the processes and factors that underlie and mediate improvements in cognitive-motor dual-task (CMDT) performance following cognitive and physical interventions in older adults.

In Study 1, we examined the cognitive and physiological mechanisms underlying CMDT improvements following executive function training, aerobic exercise, and gross motor coordination training in cognitively unimpaired older adults. We found evidence that reduced metabolic energy expenditure, and improved task-switching abilities and inhibitory control may underlie improvements in CMDT following coordination training and executive function training, respectively. Additionally, lower baseline cognitive functioning was associated with greater improvements in cognitive dual-task performance.

In Study 2, we explored potential neuroplastic changes that may accompany or underlie improvements in CMDT following EF training in middle-aged and older adults. In general, we found that increased brain activity from single-task to dual-task predicted lower dual-task costs following executive function training, consistent with a neural compensation perspective. We further found larger magnitudes of improvement in dual-task cognition following training in participants with higher baseline cognitive functioning, whereas for dual-task gait, a greater magnitude of improvement was observed in middle-aged adults with higher cognitive status, and in older adults with lower cognitive functioning.

In Study 3, we explored the effects of auditory and cognitive capacity and biological sex on CMDT performance before and after exercise, alone or combination with cognitive training, in older adults with mild cognitive impairment. We found that lower hearing ability, particularly when compounded with poorer baseline cognitive functioning, was associated with a greater magnitude of dual-task gait improvements following multi-domain exercise and cognitive training, compared to participants with better hearing and cognitive functioning. We found differential effects of hearing capacity on training efficacy across males and females depending on the nature of the hearing measure (self-report vs. behavioural).

Taken together, these findings underscore the potential for targeted cognitive and physical interventions to mitigate age-related declines in CMDT. By identifying mechanisms of change and inter-individual differences that mediate training outcomes, this work informs the design of more effective, personalized strategies to promote healthy aging.

Acknowledgements

I would like to begin by expressing my sincere gratitude to my research supervisor, Dr. Karen Li, for her invaluable guidance, unwavering support, and thoughtful mentorship throughout the course of my doctoral studies. Her expertise and encouragement have played a crucial role in shaping my academic development and the completion of this dissertation.

I would also like to extend my heartfelt thanks to my family and friends, whose love and steadfast support have been constant sources of strength throughout this journey. To my fiancé, Guillaume, and our son, Lionel—thank you for being my greatest motivation and source of joy. Your belief in me gave me the strength to keep going, even in the most challenging moments.

I would also like to acknowledge my fellow graduate students, with whom I shared the many challenges and milestones of coursework and early research. To my lab mates, thank you for your ongoing support throughout the research process. Your assistance with statistical analyses, methodological discussions, and day-to-day problem-solving was invaluable. A special note of appreciation goes to Berkley Petersen, whose friendship and encouragement were especially meaningful to me during this journey.

Finally, this work would not have been possible without the financial support provided by several funding agencies. I gratefully acknowledge my personal funding sources, including the Canadian Institutes of Health Research (CIHR), Fonds de recherche du Québec, the PERFORM Centre, Concordia University, and the Canadian Consortium on Neurodegeneration in Aging. I also acknowledge the support of my supervisor's funding from CIHR, which helped make this research possible.

Contribution of Authors

For each of the three studies presented in this dissertation, I collaborated with my supervisor, Dr. Karen Li, in formulating the research questions and designing the experimental protocols. I was responsible for developing the experimental paradigms, conducting data collection (where applicable), performing statistical analyses, and drafting the manuscripts. Further contributions are detailed below.

Study 1

Dr. Louis Bherer, Dr. Nicholas Berryman, Dr. Antony Karelis, and Dr. Anil Nigam were responsible for obtaining funding and contributed to the original study design. Dr. Kristel Pothier and Dr. Brittany Inzandt contributed to the study methodology and project administration. Dr. Maxime Lussier contributed to the development of the cognitive training program. Dr. Thomas Vincent and Tudor Vrinceanu helped with data collection. All coauthors contributed to the conceptual interpretation of the findings and provided feedback on the manuscript.

Study 2

Dr. Jennifer Campos and Niroshica Mohanathas contributed to the study conceptualization and methodology. Dr. Christophe Grova and Edouard Delaire provided their expertise on the use of functional near infrared spectroscopy. Dr. Louis Bherer and Dr. Maxime Lussier contributed to the development of the cognitive training program. Vanessa Correia and Nathan Gagné helped with project administration and data collection. Dr. Kathleen Pichora-Fuller, Dr. Natalie Phillips, Dr. Walter Wittich, Dr. Nancy St-Onge, and Dr. Jean-Pierre Gagne helped in the acquisition of funding.

Study 3

This study used data collected at various Canadian sites as part of the COMPASS-ND study and SYNERGIC trial under the Canadian Consortium on Neurodegeneration in Aging (CCNA). Dr. Karen Li, Dr. Jennifer Campos, Berkley Petersen, and Niroshica Mohanathas collaboratively contributed to the study conceptualization and research question. Dr. Manuel Montero-Odasso was responsible for obtaining funding for the SYNERGIC trial and contributed to the original study design. Dr. Louis Bherer contributed to the development and validation of the cognitive training program and the physical exercise intervention. Dr. Teresa Liu-Ambrose and Dr. Laura Middelton further contributed to the development of the exercise intervention. The remaining co-authors contributed to the process of manuscript review.

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CHAPTER ONE:

GENERAL INTRODUCTION

Population Aging

According to the World Health Organization, nearly 2 billion people will be aged 60 or over by the year 2050, almost doubling in proportion from 2015 (WHO, 2024). The growing rate of older adults is of concern as aging is associated with diminished cognitive, physical, and sensory functioning, which can limit everyday functioning and quality of life (Dalton et al., 2003; Moritz et al., 1995; Rantakokko et al., 2013). For example, older adults are at a greater risk for balance and gait impairments, as well as falls and mobility disability (i.e., inability to walk independently inside and outside of the home; Newman, 2023). The prevalence of hearing loss also increases with age, with up to two thirds of adults aged 70 years and older having bilateral peripheral hearing loss (Lin et al., 2011; Mick et al., 2021). Finally, aging is considered the largest risk factor for neurocognitive disorders, including mild cognitive impairment (MCI) and dementia (van der Flier & Scheltens, 2005). MCI is considered an intermediary stage between age-normative cognitive functioning and dementia, with annual conversion rates of MCI to dementia ranging from 10 to 15% (Petersen, 2004; Roberts & Knopman, 2013). It is estimated that 16-20% of older adults over the age of 65 live with MCI (Roberts & Knopman, 2013), whereas the global prevalence of dementia in older adults 60 years and above is between 5-7% (Prince et al., 2013). Cognitive, physical, and auditory functioning becomes increasingly interdependent with age (Li et al., 2018; Li & Lindenberger, 2002), making it imperative to understand the mechanisms underlying age-related declines and identify interventions to improve the functioning and quality of life of older adults.

Cognitive Aging

Observations of cognitive aging were noted as early as the sixth century by Solon, a Greek philosopher, who, is his poem, Elegy on the Ages of Man, described a decline in intellectual abilities starting in the “eighth stage of life” (i.e., between the ages of 56 and 63 years old; see Cokayne, 2003). Researchers have since investigated cognitive aging more rigorously by measuring cognitive performance (e.g., reaction times, accuracy) cross-sectionally across age-groups and longitudinally over time (e.g., Berlin Aging Study, Baltimore Longitudinal Study of Aging). While certain cognitive processes have been found to remain relatively stable or even improve across the lifespan (e.g. vocabulary, verbal comprehension, general knowledge; Cattel, 1963), other cognitive domains have been found to notably decline with age, including speed of processing, episodic memory, attention, and executive functioning (Craik & Salthouse, 2000). Aging is also associated with increased variability in cognitive performance, including both intra-individual (i.e., variability in performance within individuals across time) and inter-individual variability (Lindenberger & von Oertzen, 2006), with higher variability correlating with reduced cognitive performance (Bielak et al., 2010).

Executive functions have been thoroughly studied in the field of cognitive aging due their age-sensitive nature. Indeed, the prefrontal-executive theory initially proposed by Dempster & Vegas (1992) and later validated by West (1996) argues that age-related structural and functional changes in the prefrontal cortex (PFC) underlie executive function decline. Executive functions can be broadly defined as a set of higher order supervisory control processes that regulate and guide goal-directed behaviour, including several distinct, but correlated cognitive abilities such as updating, inhibition, and shifting (Miyake et al., 2000; Miyake & Friedman 2013). Updating refers to the monitoring and rapid addition/deletion of contents in working memory, inhibition is defined as the deliberate overriding of a prepotent response or suppression of task irrelevant information, while shifting refers to flexibility in switching between tasks or mental sets (Miyake & Friedman, 2013). Divided attention, or dual tasking, is another cognitive process involved in executive functioning, wherein two cognitive tasks are completed concurrently. Evidence suggests that older adults tend to demonstrate greater dual-task performance decrements compared to younger adults (Verhaeghen et al., 2003).

Cognitive aging theories. Several prominent theories have been proposed to better understand the mechanisms underlying age-related cognitive decline. According to the resource deficit hypothesis (Craik, 1986; Craik & Byrd, 1982), aging is associated with a reduction in available attentional resources, resulting in a lack of specificity for memory operations and reduced performance on cognitively demanding tasks. Another notable cognitive aging theory is the processing-speed theory (Salthouse, 1996), which posits that age-related cognitive deficits reflect a general reduction in the speed with which cognitive operations can be executed. Salthouse (1996) postulated that slow processing speed impacts cognitive performance via two mechanisms: a limited time mechanism, wherein older adults take longer to processes early operations which reduces time available for later operations, and a simultaneity mechanism, wherein older adults have difficulty considering multiple task-irrelevant components together because the products of earlier processing are not available until ongoing processing is completed. Finally, the inhibition deficit theory (Hasher & Zacks, 1988; Zacks et al., 2000) suggests that age-related cognitive deficits reflect a decline in the inhibitory control of working memory contents. Specifically, when inhibitory control is compromised, task-irrelevant information may enter working memory, leading to a disruption of working memory functions, such as encoding and retrieval of information (Zack et al., 2000).

Neuroimaging. In addition to the behavioural measurement of cognition, a large corpus of research has investigated the neural substrates underlying age-related cognitive decline. Regarding structural brain changes, aging has been associated with significant reductions in grey matter volume, particularly in the frontal cortex (Raz et al., 1997; Resnick et al., 2003; Salat et al., 1999; Tisserand et al., 2002) and hippocampus (Raz et al., 2005), which correlates with reduced performance on measures of executive functioning (Raz et al., 1998) and episodic memory (Golomb et al., 1996; Petersen et al., 2000), respectively. There is also evidence of age-related white matter changes, including a decline in cerebral white matter volume (Guttmann et al., 1998; Salat et al., 1999) and white matter integrity (Head et al., 2004; Salat et al., 2005; Sullivan et al., 2001), with the most prominent changes occurring in the frontal lobe and corpus callosum. Reduced white matter integrity has further been found to mediate age-related differences in cognitive performance (Madden et al., 2008).

Aging is also associated with changes in functional brain activity, including a bilateral upregulation of brain activity in prefrontal regions compared to younger adults (Cabeza et al., 1997, Reuter-Lorenz et al., 2000), as well as a shift of brain activity from posterior to anterior regions, with decreased activity in occipital regions and increased activity in the prefrontal cortex (Ansado et al., 2012; Grady et al., 1994). Several researchers have argued that the increased prefrontal activity observed in older adults reflects a compensatory process in response to age-related structural and functional brain changes (Cabeza et al., 2002; Park & Reuter-Lorenz, 2009; Reuter-Lorenz & Cappell, 2008). For example, the Compensation-Related Utilization of Neural Circuits Hypothesis (CRUNCH) theory posits that the level of brain activity increases with task demands to support performance, but when an older adult surpasses a threshold that exceeds their available cognitive resources (i.e.., under high task demands), brain activity and behavioural performance subsequently declines (Reuter-Lorenz & Cappell, 2008). Additionally, the Scaffolding Theory of Aging and Cognition (STAC) postulates that additional neural networks are recruited when the primary network becomes inefficient (Park & Reuter-Lorenz, 2009). The Hemispheric Asymmetry Reduction in Older Adults (HAROLD) model further suggests that under similar task demands, frontal brain activation tends to be less lateralized in older adults compared to younger adults (Cabeza et al., 2002a). Additionally, increased brain activity may act a compensatory process in response to neural dedifferentiation, characterized by reduced specificity of neural representations, particularly in the ventral visual and sensory cortices (Koen & Rugg, 2019). For example, evidence of increased frontal and decreased sensory activation has been observed in older compared to younger adults across attentional, working memory, and long-term memory tasks (Cabeza et al., 2004; Davis et al., 2007). In contrast, increased brain activation observed in older adults during cognitive tasks may also reflect neural inefficiency, whereby neural upregulation is not beneficial or is detrimental to performance. For example, it has been demonstrated that increased brain activity in older adults is associated with poorer working memory performance (Zarahn et al., 2007).

Compensatory theories of cognitive aging are supported by evidence demonstrating that increased frontal brain activity in older adults is associated with better cognitive performance (e.g., Cabeza et al., 2002b; Reuter-Lorenz et al., 2001). Individual difference factors, such as cognitive ability and brain structure, appear integral to understanding the process of age-related neural compensation. For example, researchers have demonstrated that higher fluid intelligence in older adults is associated with increased cortical thickness (Fjell et al., 2006) and that greater mid-life memory improvements (i.e., improvements observed between the ages of 43-63 years old) are associated with reduced hippocampal atrophy in late adulthood (Borghesani et al., 2012). Regarding functional brain activity, Pudas et al. (2013) demonstrated that over a 15-to-20-year period, older adults who had preserved memory functioning had higher hippocampal and prefrontal activity, compared to individuals with average memory declines. These results help elucidate the factors that might stimulate age-related neural compensation, while also highlighting potential sources for variability in cognitive aging.

Interventions. Given the functional implications of age-related cognitive decline, a central focus of investigation has been on interventions to improve cognitive functioning in older adults. Regarding computerized cognitive training, there are mixed results in the literature, with evidence from some, but not all, studies demonstrating improvements in cognitive functioning in cognitively impaired and unimpaired older adults (Kueider et al., 2012; Martin et al., 2011; Papp et al., 2009; Reijnders et al., 2013). The lack of consistency in training efficacy within the literature may reflect heterogeneity across studies, including differences in the cognitive processes that are targeted with training, the cognitive outcome measures that are evaluated, and the frequency and duration of training sessions. Nevertheless, there appears to be relatively large training effects for executive function training on trained outcomes, with a smaller magnitude of improvement on near-transfer tasks, followed by far-transfer tasks (Karbach & Verhaeghen et al., 2014; Nguyen et al., 2019a). Near-transfer refers to improvements in skills that are highly similar and overlap with the cognitive training, whereas far-transfer refers to improvements in skills that overlap less with the cognitive training (e.g., involve more abstract or different domains), but may involve similar underlying cognitive processes. Executive function training has been found to lead to near-transfer effects in cognitively unimpaired older adults, including improvements in inhibitory control, divided attention, and task-switching (Bherer et al., 2021; Desjardins-Crepeau et al., 2016).

Changes in brain activity following executive function training have also been found to predict improvements in cognitive performance, including increased hemispheric asymmetry and reduced prefrontal cortex activation (Erickson et al., 2007; Pellegrini-Laplagne et al., 2023), as well as increased frontal, parietal and temporal activation from pre- to post-training (Adnan et al., 2017). There is also evidence for a shift in brain activation following practice (on a verbal production task and maze learning task), where skills become better consolidated and less effortful (i.e., frontal activation reduces and becomes more efficient following training; Petersen et al., 1998). However, the exact time-course and maintenance of training-related brain and performance changes remains unclear.

There is now mounting evidence for the effect of exercise interventions in improving cognitive performance, particularly executive functions, in older adults. For example, aerobic exercise has been shown to improve inhibitory control and working memory (Colcombe & Kramer, 2003), with a similar magnitude of improvement in executive functioning observed across low-to-medium and high intensity aerobic exercise (Moreau & Chou, 2019). Structural and functional brain adaptations have also been observed in older adults following aerobic exercise compared to non-aerobic exercise (i.e., stretching and toning exercises), including increased grey and white matter volume (Colcombe et al., 2006), as well as increased activity in frontal and parietal regions with a concomitant decrease in activity in the anterior cingulate cortex (Colcombe et al., 2004). Resistance training has also been found to improve executive functions, including inhibitory control, working memory and cognitive flexibility (Huang et al., 2022; Soga et al., 2018), as well as evoke structural and functional brain changes, such as reduced white matter atrophy, reduced white matter lesion volumes, and lower prefrontal cortex activity (Herold et al., 2019). Researchers have further demonstrated improvements in cognitive functioning (e.g., episodic memory, global cognition) following multicomponent exercise interventions involving resistance, balance, and gait training in older adults with MCI (Suzuki et al., 2012; 2013). Finally, gross motor coordination training has been shown to improve inhibitory control (Forte et al., 2013), with parallel reductions in prefrontal cortex activity (Voelcker-Rehage et al., 2011). Potential pathways mediating neurocognitive improvements following exercise include increased cardiovascular efficiency (Bherer et al., 2021; Stillman et al., 2016), neurochemical stimulation (e.g., dopamine, serotonin, brain-derived neurotrophic factor; Cheng et al., 2022; Stillman et al., 2016), and structural and functional brain changes, as described.

When considering interventions to improve cognitive functioning in older adults, the following question is often raised: “What individual difference factors promote the greatest magnitude of improvement following training?”. Grounded in research on mnemonic training, Lövden et al. (2012) proposed a conceptual framework to elucidate this question, with two opposing views according to the level of cognitive resources available to the individual (i.e., magnification vs. compensation). Regarding magnification, Lövden et al. (2012) posit that individuals with higher baseline levels of cognitive resources gain more from training due to the increased capacity to acquire, implement, and refine effortful cognitive strategies. This view is empirically supported by research demonstrating positive correlations between cognitive abilities and magnitude of improvements from mnemonic training (e.g., Kliegl et al., 1990; Verhaegen & Marcoen, 1996). In contrast, the compensation account of training proposes that individuals with lower baseline cognitive functioning or who utilize inefficient cognitive strategies prior to training will have greater opportunity for improvement from training (Lövden et al., 2012). Support for the compensation view comes from research demonstrating negative correlations between cognitive abilities and mnemonic training gains (e.g., Cox, 2001; Gaultney et al., 1996). Outside of mnemonic training, research in the field of cognitive aging generally supports the compensation view following working memory and executive function training, with older adults with lower baseline cognitive functioning showing the greatest magnitude of improvement

(Hering et al., 2017; Shaw & Hosseini, 2021). Consistent with this line of questioning, other individual differences factors, such as physical functioning and hearing ability, may also impact training efficacy, due to their interactions with cognitive functioning, as described below.

Motor Aging

Another central aspect of healthy aging is the maintenance of mobility, including gait and balance. Gait, or the forward walking movement of the body, can be measured experimentally by instrumented walkways with embedded pressure sensors, footswitch sensors which are placed under the soles of the feet, or the use of a stopwatch. Gait measurements can be evaluated according to temporal characteristics, such as gait speed, stride time (i.e., time elapsed between the first contact of two consecutive footsteps), and double support time (i.e., portion of stride time when two feet contact the ground simultaneously), spatial characteristics, such as stride length (i.e., average distance between successive footfalls), as well as gait variability (i.e., standard deviation or coefficient of variation of temporal or spatial gait parameters). Balance is typically assessed under static (e.g., single- or double-support standing) or dynamic conditions, wherein individuals are required to react to an environmental event such as a perturbation. Balance is typically quantified according to deviations in performance over time, including centre of mass (i.e., the point where the entire mass of the individual is concentrated) and centre of foot pressure (point where the total force acting on an individual’s feet is concentrated) distance, as well as variability in performance.

Aging is associated with a decline in both gait and balance, including slowed gait speed, reduced step length, and increased double-support time (Elble et al., 1991; Winter et al., 1990) as well as increased upright postural sway, increased falls, and increased likelihood of initiating a stepping strategy following a postural perturbation at lower levels of challenge (i.e., slower perturbation velocity; Brown et al., 1999; Jensen et al., 2011). Age-related mobility changes partly reflect a decline in one's physical capacity with age, including reduced muscle mass and strength (Lauretani et al., 2003), maximal oxygen consumption (Schrack et al., 2011), and joint flexibility (Nolan et al., 2010). However, while gait and balance were once considered to be largely automatic tasks, it is now well-established that one's cognitive functioning also plays a pivotal role in the maintenance of mobility in old age (e.g., Demnitz et al., 2016; Hausdorff et al., 2005; Woollacott & Shumway-Cook, 2002).

Cognitive involvement. Evidence for the involvement of cognition in gait and balance in late adulthood partly stems from cross-sectional correlational studies, which have demonstrated moderate associations between cognitive functioning and gait and balance measures. For example, studies have shown that in older adults, poorer executive functioning is associated with reduced gait speed, increased gait variability, and increased risk for falls (see Demnitz et al., 2016 for review; Kearney et al., 2012). While other cognitive processes, such as memory and processing speed, also correlate with gait performance, the effect sizes tend to be smaller (Demntiz et al., 2016). There is also some evidence of a positive relationship between gait speed and cognitive functioning in mid-life (i.e., 45-years-old; Rasmussen et al., 2019). Balance performance in older adults has also been found to correlate with cognitive functioning, including executive functioning and dynamic (small to moderate effect sizes) and static (small effect sizes) balance, as well as processing speed and dynamic balance (see Divandari et al., 2023 for review).

Cognitive-motor dual tasking. Experimental studies implementing a cognitive-motor dual-task design (i.e., the simultaneous completion of a cognitive and motor task) have further advanced our knowledge of the cognitive involvement in gross motor control. This line of research was instigated in a seminal study by Lundin-Olsson et al. (1997) who demonstrated that in older nursing home residents, the inability to maintain a conversation while walking predicted future fall risk. To measure divided attention proficiency with dual-task designs, performance is compared across single-task (i.e., cognitive and motor tasks are completed alone, with full attention) and dual-task (i.e., cognitive and motor tasks are completed concurrently, with divided attention) conditions. Dual-task costs can be calculated as either absolute costs (e.g., dual-task minus single-task) or proportional costs (e.g., [dual minus single-task] / single-task).

There is now a corpus of evidence demonstrating a reduction in gait (e.g., reduced gait speed), balance (e.g., increased centre of pressure area), and cognition (e.g., increased reaction times) under dual-task, compared to single-task conditions in older adults (for reviews see Al-Yaha et al., 2012; Boisgontier et al., 2013; Smith et al., 2017; Smith et al., 2016; Yogev-Seligmann et al., 2008; Woollacott & Shumway-Cook, 2002). Dual-task costs tend to be greater in older adults and in populations with cognitive (e.g., MCI, Alzheimer's Disease) or motor (e.g., Parkinson's Disease) impairments compared to younger adults (Fritz et al., 2015; Montero-Odasso et al., 2012a; Yogev-Seligmann et al., 2008).

Dual-task costs are further exacerbated under more challenging conditions, such as increased cognitive load or increased balance difficulty (Little & Woollacot, 2014; Smith et al., 2017). Notably, not all secondary cognitive tasks are detrimental to mobility. For example, under low cognitive load conditions (e.g., serial one subtractions), both younger and older adults demonstrate improved gait and balance performance compared to single-task conditions (Huxhold et al., 2006; Li et al., 2012; Lövden et al., 2008). One interpretation of these findings is that devoting full attention to highly automated tasks such as balancing and walking (i.e., under single-task conditions) is unnatural, leading to decrements in performance, whereas a low cognitive load may lead to a greater external focus of attention and facilitate gait and balance. However, at higher levels of cognitive complexity, resource competition becomes detrimental to motor performance. Of note, the point of inflection, wherein the cognitive task begins to interfere with mobility performance, appears to occur at lower levels of cognitive task complexity in older adults compared to younger adults, possibly due to reduced cognitive and neural resources with age, causing greater competition amongst resources while dual tasking (Huxhold et al., 2006; Lövden et al., 2008).

Another important consideration in the dual-task literature is task prioritization, which examines the tendency of prioritizing the motor (i.e., "posture-first" strategy or postural prioritization) or cognitive task (i.e., "posture-second" strategy) while dual tasking. The concept of postural prioritization was first presented by Shumway-Cook et al. (1997) and was further substantiated in a study by Li et al. (2001), who demonstrated that older adults spontaneously prioritized walking to the detriment of the secondary cognitive task. Evidence of postural prioritization in older adults has since been replicated in several studies (e.g., Brown et al., 1999; Li et al., 2012; Verghese et al., 2007) and has been speculated to reflect an adaptive strategy to avoid hazards and prevent falls while walking or balancing. However, factors such as task complexity and level of cognitive and physical resources have been found to moderate postural prioritization (see Yogev-Seligmann, et al., 2012 for review). For example, studies have demonstrated that with increasing task complexity, dual-task costs are more pronounced in the cognitive domain, consistent with postural prioritization (Brown et al., 2002; Doumas et al., 2008). While some research has shown that postural prioritization is preserved in older adults with cognitive impairment (i.e., Alzheimer's Disease; Rapp et al., 2006), other evidence suggests that older adults with reduced cognitive and physical functioning (e.g., MCI, Parkinson's

Disease) adopt a posture-second strategy while dual tasking, which may be maladaptive, unintentionally exacerbating the risk of falling (Bloem et al., 2006; Lee & Park, 2018). Taken together, dual-task research provides compelling evidence for the involvement of cognition in mobility in late adulthood, and highlights important factors for consideration, such as task complexity and individual differences in cognitive and physical capacity.

Longitudinal studies have further elucidated the temporal relationship between cognitive and mobility decline with age. For example, changes in gait parameters, such as slowed gait speed and increased gait variability, have been shown to predict cognitive decline across several domains (Beauchet et al., 2014), as well as incident MCI (Buracchio et al., 2010) and dementia (see Beauchet et al., 2016 for review). Additionally, slower baseline gait speed predicts a greater magnitude of cognitive decline over time (Best et al., 2016; Mielke et al., 2013; Tian et al., 2017). Conversely, poorer cognitive functioning, particularly executive functioning, is a risk factor for future falls (Mirelman et al., 2012) and faster rates of decline in gait speed (Soumaré et al., 2009) and global mobility (Inzitari et al., 2007). It has also been shown that falls risk, and balance and mobility decline are greater in older adults with dementia compared to cognitively unimpaired older adults (Suttanon et al., 2013). Finally, poor dual-task performance is associated with an increased risk for falling (Montero-Odasso et al., 2012b; Muir-Hunter & Wittwer, 2016) and cognitive decline, including mild cognitive impairment (MCI) and dementia (Montero-Odasso et al., 2017).

Neuroimaging. Converging evidence for the role of cognition in gait and balance with age is found in research implementing structural and functional brain imaging. For example, using magnetic resonance imaging (MRI), slow gait speed has been associated with reduced overall grey matter volume, as well as reduced grey matter volume in the hippocampus, frontal cortex, basal ganglia, and cerebellum (see Wilson et al., 2019 for review). Less consistent results have been found for the association between grey matter volume and other gait characteristics (e.g., stride time, double support time, step and stride time variability; Wilson et al., 2019). Balance difficulties in older adults has also been shown to negatively correlate with grey matter volumes in the putamen, posterior superior parietal cortex, and cerebellum (Rosano et al., 2007). Finally, there is some evidence that slower gait speed and higher gait variability are associated with increased white matter hyperintensities (i.e., lesions that are often manifestations of cerebrovascular disease) in older adults (Wilson et al., 2019).

In examining the relationship between brain structure, cognition, and mobility, Rasmussen et al. (2019) demonstrated that in mid-life (i.e., 45-years-old), poorer cognitive functioning (e.g., poorer semantic fluency, mental-set shifting) was associated with smaller total brain volume, smaller total brain surface, and slower gait speed. Additionally, structural brain changes in older adults (e.g., thinner temporal cortex and shallower sulcal depth in the frontal, sensorimotor, and parietal cortices) have been found to correlate with increased gait dual-task costs (Hupfeld et al., 2022). Smaller brain volumes in older adults with cognitive impairment (e.g., MCI, Alzheimer's Disease) have further been found to correlate with higher cognitive dual-task costs, with no relationship found between gait dual-task costs and brain volumes (Longhurst et al., 2020). In longitudinal designs, researchers have found that over time, a decline in overall white matter volume is associated with a reduction in step length (Callisaya et al., 2013; van der Holst et al., 2018), and that smaller baseline white matter volume predicts a greater decline in gait speed over time (Ryberg et al., 2011; Wolfson et al., 2005). Additionally, smaller hippocampal volume has been directly implicated in the relationship between gait slowing and cognitive decline over time (Rosso et al., 2017).

Regarding functional brain activity, various methodologies have been employed to elucidate the underlying neural mechanisms of balance, gait, and dual-task performance. For example, researchers have measured neural activity during tasks of imagined walking using functional magnetic resonance imaging (fMRI), correlated electroencephalography (EEG) findings with motor outcomes, measured the uptake of glucose while engaged in a motor task using positron emission topography (PET), or measured changes in oxygenated (HbO) and deoxygenated hemoglobin (HbR) levels during real-time locomotion and balance tasks using functional near infrared spectroscopy (fNIRS; Hamacher et al., 2015; Purohit & Bhatt, 2022).

Current evidence suggests that gait and balance are associated with increased brain activity in the prefrontal cortex, premotor cortex, and supplementary motor area, with a greater magnitude of neural upregulation observed in older adults and in individuals with neurodegenerative conditions, such as PD (Hamacher et al., 2015; Stuart et al., 2018). Additionally, under dual-task conditions, there is a relative increase in cerebral oxygenation in the PFC compared to single-tasking (Hamacher et al., 2015; Kahya et al., 2019). However, there is inconsistent evidence on whether this increase in neural activity is more pronounced in older adults (see Kahya et al., 2019, Pelicioni et al., 2019, and Udina et al., 2020 for reviews). Some studies have demonstrated increased PFC activity while dual-task walking in healthy older adults compared to younger adults (Mirelman et al., 2017; Ohsugi et al., 2013), whereas other studies have failed to demonstrate significant age effects on brain activity (Fraser et al., 2016; Marusic et al., 2019; Stuart et al., 2018), and still other studies have found that younger adults have higher brain activity while dual tasking compared to older adults (Beurskens et al., 2014; Holtzer et al., 2011). These inconsistencies highlight the importance of examining the relationship between brain activity and performance to elucidate whether changes in brain activity with age reflect neural compensation or inefficiency.

Indeed, like the cognitive aging literature, a central question in the field of mobility has been on examining whether increased brain activity correlates with better or worse mobility performance (reflecting neural compensation or neural inefficiency, respectively). Within the single-task gait literature, there appears to be greater evidence of neural compensation in older adults (see Fettrow et al., 2021 for review). For example, studies have shown that greater brain activity (measured during offline cognitive tasks completed in an MRI), correlates with better gait performance (Jor'dan et al., 2017; Kawagoe et al., 2015), consistent with neural compensation. In contrast, Fernandez et al. (2019) demonstrated that in older adults at high risk of falling, increased brain activity in the parietal-occipital sulcus and precuneus during an offline selective attention task was associated with higher gait variability, suggestive of neural inefficiency. These findings highlight the importance of considering individual difference factors, such as level of physical resources, which may impact the observation of neural compensation or inefficiency.

Evidence for neural compensation or inefficiency appears more mixed in the dual-task gait literature. Specifically, some researchers have found that a greater increase in brain activity from single-task to dual-task is associated with lower gait speed dual-task costs in healthy older adults (Maidan et al., 2016), and better offline inhibitory control in older adults with MCI (Doi et al., 2013), consistent with neural compensation. In contrast, other studies have found evidence of neural inefficiency, whereby greater increases in brain activation during dual tasking have been associated with higher gait speed dual-task costs in older adults with PD (Maidan et al., 2016), and greater cognitive and gait dual-task costs in healthy older adults (Stojan et al., 2023).

Similarly, Ross et al. (2021) demonstrated that in healthy older adults, reduced cortical thickness in regions implicated in higher order control of gait was associated with increased PFC activity while dual tasking, without associated benefits to behavioural performance, suggestive of neural inefficiency. In examining variability rather than average activation levels (i.e., changes in brain activity throughout the duration of the task) in older adults, Holtzer et al., (2020) demonstrated that increased intraindividual variability in PFC activity during dual-task walking correlated with increased gait variability, possibly reflecting an inefficient neural response. Interestingly, the presence of cognitive impairment and being a male were independently associated with increased variability in neural activity, highlighting the importance of considering individual difference factors such as sex and cognitive status. Future research that considers the level of task difficulty and level of resources available to the individual may help elucidate these inconsistencies. For example, it could be speculated that a certain capacity-demand threshold is needed to observe neural compensation, whereas once demands significantly surpass available resources, a pattern of neural inefficiency may be evident.

Interventions. Evidence for the involvement of cognition in mobility has instigated research to examine the effect of cognitive and physical interventions in improving cognitive, motor, and functional outcomes in late adulthood. Studies implementing commercialized cognitive training programs that target multiple cognitive processes (e.g., divided attention, processing speed, working memory) have demonstrated improvements in single- and dual-task gait speed (Verghese et al., 2011) and functioning mobility (i.e., Timed Up and Go; TUG), particularly in frail older adults (Smith-Ray et al., 2014) and older adults categorized as slow walkers (Smith-Ray et al., 2015). Li et al. (2010) further demonstrated improvements in balance performance (i.e., postural sway under single-task and dual-task conditions, center of pressure alignment during double-support dynamic balance) in older adults following five sessions of computerized divided attention training. Results from a systematic review and meta-analysis examining the effect of cognitive interventions on mobility in older adults demonstrated significant improvements in dual-task gait speed (small effect size), but not single-task gait (Marusic et al., 2018). Physical exercise interventions have also proven beneficial in improving cognition and cognitive-motor dual-task performance in older adults (see Plummer et al., 2015 and Lipardo et al., 2017 for reviews).

There is currently mixed evidence for the potential synergistic effects of multi-domain training that combines cognitive and physical interventions on cognitive, functional and dual-task outcomes in older adults. For example, in a series of studies comparing different combinations of active and control treatment arms (i.e., aerobic-resistance training, balance and stretching exercises, divided attention training, sham cognitive training), improvements were observed in functional mobility (e.g., 6-meter walk test), cognition (e.g., processing speed, inhibitory control), and dual-task gait speed, though there were limited training interaction effects, suggesting a similar magnitude of improvement across single- vs. multi-domain treatment arms (Desjardins-Crépeau et al., 2016; Fraser et al., 2017). In contrast, in a study implementing the same intervention protocol, Bherer et al. (2019) demonstrated a synergistic effect of aerobic exercise and resistance training with divided attention training in improving performance on a near-transfer executive function task (i.e., reduced task-set costs). Additionally, Montero-Odasso et al. (2023) found significant improvements in global cognitive functioning following aerobic exercise and resistance training with executive function training in older adults with MCI. Thus, it remains unclear whether multi-domain cognitive and physical training confers synergistic effects on cognitive and dual-task performance in older adults.

A final body of research has investigated the effect of cognitive-motor dual-task training (i.e., exercise with concurrent cognitive training) on cognitive and physical outcomes in older adults. In two systematic reviews, Wollesen et al. (2014; 2020) identified significant improvements in global cognitive functioning, executive functioning, and cognitive-motor interference (in both cognitive and motor tasks), with a greater magnitude of improvement observed following interventions that combined cognitive training with multi-component exercises. Interestingly, in comparing multi-domain versus dual-task training (i.e., simultaneous versus sequential delivery of executive function and aerobic exercise training), researchers have found a greater magnitude of improvement in single- and dual-task working memory performance in older adults following sequential versus simultaneous training (Bruce et al., 2019b; Lai et al., 2017). The authors speculated that these results may reflect increased cognitive interference during dual-task training, potentially limiting the benefits of the intervention.

Various mechanisms have been proposed to underlie training-related improvements in cognition and mobility. For example, cognitive training is proposed to lead to improvements in gait and balance via increased divided attention and inhibitory control (Li et al., 2010; 2018). Physical exercise is further suggested to improve cognitive functioning via neurochemical stimulation (e.g., dopamine, serotonin, brain-derived neurotrophic factor; Cheng et al., 2022; Stillman et al., 2016), increased cardiorespiratory fitness following aerobic exercise (Bherer et al., 2021), increased muscular strength following resistance training (Mavros et al., 2017), reduced metabolic expenditure following gross motor balance and coordination training (Van Swearingen & Studenski, 2014), and structural and functional brain adaptations (see Bherer et al., 2013 and Herold et al., 2019 for reviews). Nevertheless, empirical support for such mechanisms largely stems from research investigating independent cognitive and motor outcomes. Given the involvement of cognition in mobility in late adulthood, understanding the putative mechanisms underlying improvements in cognitive-motor dual-task performance following training is imperative. For example, cognitive and physiological changes following training may be independently associated with improvements in cognitive-motor dual-task performance, or these mechanisms might overlap.

Neural adaptations may also underlie or accompany mobility or dual-task improvements following cognitive or physical training, though this is a relatively underexplored area of research, with some conflicting findings. For example, Marusic et al. (2022) implemented EEG in a sample of healthy older adults and found that following computerized cognitive training, reduced P2 latency (i.e., shortening of a visual-evoked potential component) during an offline sensorimotor task was associated with faster dual-task gait speed. This may reflect a reduced level of neural activation required following training, consistent with a pattern of neural efficiency. Outside of the cognitive training literature, Holtzer et al. (2019) previously demonstrated decreased prefrontal activation in older adults following repeated practice of dual-task walking. The authors speculated that initial increases in prefrontal activity may act as a compensatory mechanism to maintain dual-task gait performance, but as learning progresses and the task becomes less effortful, fewer cognitive and neural resources may be required to support performance (Holtzer et al., 2019). These findings echo those described by Petersen et al. (1998) who demonstrated a reduced reliance on prefrontal regions following practice of a skill. Of note, Holtzer et al. (2019) further demonstrated that older adults who reported a fear of falling showed less of a reduction in prefrontal activity following repeated trials, highlighting the need to consider individual difference factors, such as level of capacity, when interpreting the brain-behaviour relationship.

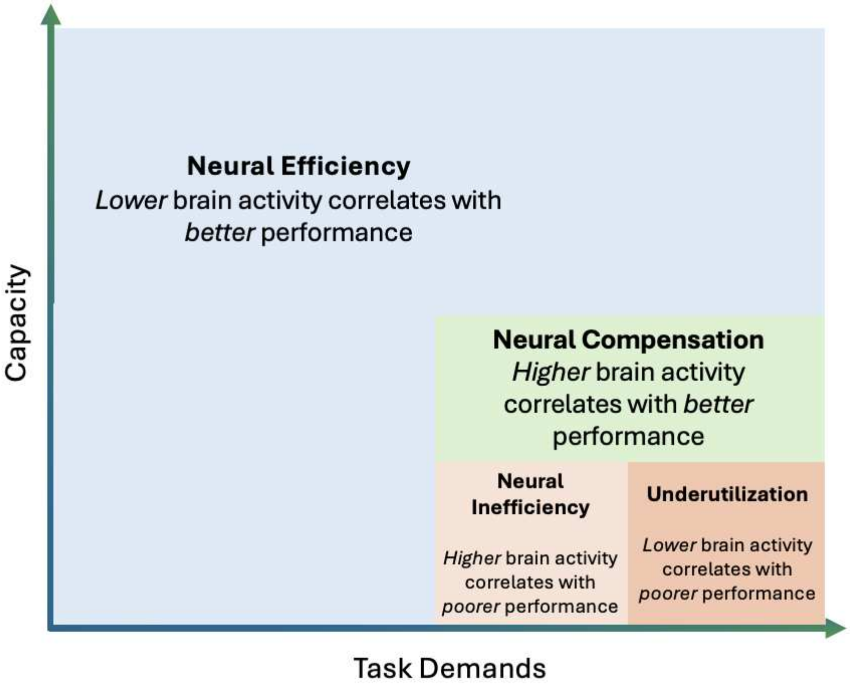
Indeed, studies of older adults with cognitive impairment tend to show a pattern of neural compensation following cognitive training. For example, in a study by Kuo et al. (2022) that included older adults with MCI, the authors found that following cognitive dual-task training (i.e., walking while concurrently completing cognitive tasks), improvements in cognitive-motor dual-task stride length correlated with an increase in activity in the PFC, premotor cortex (PMC), and supplementary motor area (SMA). Additionally, improvements in motor-motor dual-task performance (i.e., cadence) were observed following cognitive dual-task training, which positively correlated with activity in the PFC and right PMC. These findings appear more consistent with a compensatory neural process underlying training-related improvements. Finally, in a sample of older adults with Alzheimer's Disease (AD), Parvin et al. (2020) demonstrated improvements in functional mobility, gait, and muscle strength, as well as an increase in offline brain oscillations in the occipital lobe and a decrease in the theta/alpha ratio following multi-domain physical and cognitive training. The authors noted that higher alpha oscillation frequency correlates with increased cerebral blood flow (Parvin et al., 2020), so while there were no direct correlations made between the behavioural and neural measures, it could be speculated that training may have led to increased brain activity and motor performance, which would be more consistent with neural compensation.

Taken together, evidence for the neural processes underlying mobility-related improvements following cognitive and physical training is limited but may be influenced by level of cognitive resources available to the individual. For example, in cognitively impaired older adults with fewer cognitive resources, training may stimulate compensatory neural scaffolding to improve performance, whereas in cognitively unimpaired individuals, higher levels of cognitive resources may allow for increased neural efficiency following training (see

Figure 1 for a conceptual framework). Nevertheless, further research is needed to help elucidate the neural processes underlying training-related improvements on dual-task performance in older adults.

Figure 1

Conceptual Framework of Brain-Behaviour Relationship During Cognitive-Motor Dual-Tasking Based Upon Capacity-Demand Threshold



Neural efficiency. Task demands are consistent with or fall below level of resources.

Increased efficiency and reduced reliance on compensatory scaffolding with training or practice in older adults with higher capacity.

Neural compensation. Task demands slightly exceed available resources.

Can occur during learning or task acquisition in older adults with higher capacity or following extended training in older adults with lower capacity.

Neural inefficiency / underutilization of resources. Resources are not sufficient to meet task demands (e.g., MCI, AD, PD, high falls risk, brain atrophy).

Note. MCI: Mild cognitive impairment; AD: Alzheimer's Disease; PD: Parkinson's Disease

Auditory Aging

In addition to cognitive and motor decline, aging is also associated with changes in sensory functioning, including vision and hearing loss. Of note, while there is a relatively high global prevalence (12.6%) of older adults over the age of 50 who experience avoidable vision loss (Steinmetz et al., 2021), the focus of this dissertation is on hearing loss. The rationale for investigating hearing loss is the increased association between hearing loss and cognitive decline, compared to visual loss (Livingston et al., 2024). Additionally, there appears to be greater potential for cognitive-motor dual-task improvements following cognitive and physical interventions in older adults with hearing loss compared to vision loss based upon the proposed mechanisms underlying the relationship between age-related auditory, cognitive, and motor functioning (see below for more details).

According to Statistics Canada, 78% of adults over the age of 60 experience hearing loss (Bizier et al., 2016). The most common form of hearing loss in older adults is presbycusis, or age-related hearing loss (Huang & Tang, 2010). Presbycusis is a form of sensorineural hearing loss which can result from degeneration of the organ of Corti, a receptor organ located in the inner ear to detect sound vibration sent from the eardrum (Lee, 2013). In the organ of Corti, sounds waves are normally transduced into a neural impulse via inner hair cells, and then the sound is amplified via outer hair cells (Lee, 2013). With presbycusis, degeneration of the organ of Corti can result in a loss of hair cells in the high-frequency region of the basilar membrane (Wingfield et al., 2005). This can lead to bilateral high-frequency hearing loss which alters the ability to detect, identify, and localize sounds, and makes speech comprehension and communication challenging (Huang & Tang, 2010).

Hearing loss has a complex etiology, with influences from both intrinsic and extrinsic factors. Intrinsic factors that can impact hearing loss include age, sex, and genetic modifiers. Hearing difficulties typically emerge in mid-life (e.g., reduced hearing sensitivity and speech in noise perception), and progressively worsen with advancing age (Brant & Fozard, 1990; Helfer & Jesse, 2021). Age-related changes in the ear, such as increased fluid or infections in the middle ear and accumulation of earwax, can also contribute to conductive hearing loss, or the obstruction of the transmission of sound waves between the middle ear and external ear canal (Walling & Dickson, 2012). Noise exposure is the most extensively studied environmental factor contributing to hearing loss. Prolonged noise exposure initially reduces the number of outer hair cells, but with continued noise exposure can lead to a loss of inner hair cells, causing noise-induced hearing loss (Liu & Dan, 2007). Finally, there are known sex differences in hearing loss, with hearing sensitivity declining earlier and more than twice as rapidly in males compared to females (Pearson et al., 1995). Both gender and biological sex factors may contribute to the observed differences in hearing sensitivity, including increased noise exposure in male-dominated occupations (Lie et al., 2016), as well as increased estrogen in females which may protect against hearing loss until menopause is reached (Nolan, 2020).

Hearing sensitivity is commonly measured using pure-tone audiometry, which involves examining the audibility of tones presented at various decibel levels and frequencies and allows for the calculation of a pure tone average (PTA) in decibels (dB) hearing loss (HL). According to the World Health Organization, grades of hearing loss are categorized as follows: normal hearing: < 20 dB, mild hearing loss: PTA of 20 to < 35 dB, moderate hearing loss: 35 to < 50 dB, moderately severe hearing loss: 50 to < 65 dB, severe hearing loss: 65 to < 80 dB, and profound hearing loss: 80 to < 95 dB (WHO, 2021). While PTA typically captures peripheral hearing loss, which involves the detection and transmission of sound signals up until they reach the auditory nerve (e.g., inner, middle, and outer ear, as described thus far), speech in noise tests allow for the measurement of central, or suprathreshold, hearing, which refers to the processing of sound signals in the auditory cortex of the brain (Powell et al., 2022).

Cognitive and motor involvement. As previously described, cognitive, motor, and auditory functioning become increasingly interdependent with age. Evidence for this relationship stems from seminal work from the Berlin Aging Study, whereby researchers demonstrated an association between sensory (vision, hearing: pure tone audiometry) and motor (gait speed, balance) aging with intellectual functioning (Baltes & Lindenberger, 1997; Lindenberger & Baltes, 1994). Several studies have since replicated and extended these findings, showing that hearing loss is associated with reduced cognitive performance (e.g., global cognition, executive functioning, processing speed, memory), accelerated cognitive decline, and incident cognitive impairment, such as dementia (Brewster et al., 2021; Lin et al., 2013; Livingston et al., 2024; Loughrey et al., 2018; Wei et al., 2018), as well as postural instability and an increased risk of falls in older adults (Agmon et al., 2017; Campos et al., 2018; Carpenter & Campos, 2020; Foster et al., 2022). Notably, Pupo et al. (2022) demonstrated that hearing loss predicts poor mobility, particularly in individuals with lower cognitive performance, further highlighting the interdependence across cognitive, motor, and auditory domains with age. Finally, greater decrements in cognitive-motor dual-task performance have been found in older adults with hearing loss compared to those with normal hearing (see Wunderlich et al., 2024 for review).

The effect of hearing ability on cognition has also been examined experimentally, where the acoustic challenge is increased (e.g., degraded speech, speech-in-noise tasks). Several studies have demonstrated that sensory manipulations that degrade hearing reduce memory encoding, with degraded hearing being more detrimental to cognitive performance in older adults compared to younger adults (e.g., Murphy et al., 2000; Pichora-Fuller et al., 1995; Rabbit, 1968; Suprenant, 2007). Bruce et al. (2019a) further investigated the effect of background noise on cognitive-motor dual-task performance in younger and older adults. The authors found reduced dual-task working memory performance during the noisy versus quiet condition, with the noise effect being magnified in older adults with hearing loss compared to older and younger adults with normal hearing, even after controlling for hearing acuity (Bruce et al., 2019a). Of note, dual-task postural performance was relatively stable across the noisy and quiet conditions in older adults with hearing loss, suggestive of a postural prioritization strategy (Bruce et al., 2019a).

Neuroimaging. Hearing loss has also been shown to impact brain structure and function. For example, studies have shown that hearing loss, particularly in high frequency ranges, is associated with smaller total brain volume (Rigters et al., 2017), reduced grey matter volume in the auditory cortex in middle-aged (Hussain et al., 2011) and older adults (Eckert et al., 2012), and reduced hippocampal and entorhinal cortex volumes (Uchida et al., 2018; Xu et al., 2019). Longitudinal studies have further shown that hearing loss is associated with a greater volumetric decline in the right temporal grey matter, right hippocampus, and left entorhinal cortex in participants with midlife hearing loss (Armstrong et al., 2019), accelerated volumetric declines in the whole brain and temporal lobe in older adults (Lin et al., 2014), as well as increased rates of atrophy in the hippocampus and entorhinal cortex in older adults (Xu et al., 2019). Changes in white matter integrity with hearing loss have also been observed. For example, Rigters et al. (2018) found that poorer hearing acuity in middle-aged and older adults correlated with poorer white-matter microstructure in the association tracts (i.e., right superior longitudinal fasciculus and the right uncinate fasciculus). Using a longitudinal design, Armstrong et al. (2020) further demonstrated that poorer peripheral hearing correlated with reduced white matter integrity in the left posterior limb of internal capsule and the left inferior fronto-occipital fasciculus, whereas poorer central hearing was associated with reduced white matter integrity in the left cingulum, uncinate fasciculus, and left column and body of the fornix.

Regarding functional brain changes, researchers have found that poorer hearing acuity is associated with reduced neural activity in some brain regions, including the superior temporal gyri, thalamus, and brainstem (Peele et al., 2011), though increased brain activity in other brain regions, such as the left middle frontal gyrus (MFG) and anterior cingulate cortex (Eckert et al., 2008). Eckert et al. (2008) further found that smaller temporal lobe volume predicted increased MFG activity, suggesting a possible recruitment of frontal regions in response to declining structural brain integrity in regions important for word recognition. Indeed, in examining age-related functional brain differences, Peele et al. (2010) found that relative to younger adults, older adults showed reduced recruitment of regions important for sentence processing (i.e., left inferior frontal gyrus), but increased activity in other frontal regions outside of the core sentence-processing network. The authors speculated that the increased frontal brain activity could reflect a compensatory process to support the working memory demands related to sentence comprehension (Peele et al., 2010). Additionally, in studies where speech is degraded, researchers have found that reduced speech intelligibility is associated with increased activity in prefrontal and premotor regions (Davis & Johnsrude 2003; Obleser et al., 2007). Taken together, these findings suggest a possible coupling between sensory ability, structural integrity, and functional reorganization, with increased recruitment of frontal executive systems as a possible pathway to maintain successful comprehension (see Peele & Wingfield, 2016 for review).

Theories. Several theories have been proposed to explain the relationship between auditory and cognitive functioning with age, which have since been applied and extended to include interactions with motor functioning. According to the common cause hypothesis, a single factor is suggested to account for the shared variance across hearing and cognitive functioning in older adults, including age-related neural degeneration, reduced processing speed, neurodegenerative pathology, vascular factors, and genetics (Baltes & Lindenberger, 1997; Lindenberger & Baltes, 1994). The sensory deprivation hypothesis suggests that prolonged auditory underload can lead to morphological and functional brain changes, such as temporal lobe atrophy and the re-allocation of attentional resources to compensate for a reduced auditory signal (Lindenberger & Baltes, 1994; Powell et al., 2022). This may lead to a reduction in the cortical capacity available for cognitive processing, and, by extension, the regulation of posture and gait. According to information degradation or effortful listening theories, hearing loss increases the cognitive complexity and demands associated with listening, leading to the recruitment or reallocation of attentional resources to comprehend an impoverished auditory signal (Lindenberger & Baltes, 1994; Pichora-Fuller et al., 2003; Schneider & Pichora-Fuller, 2000). This may result in increased competition for the same resources needed for other tasks requiring higher-order cognitive processing, such as mobility. Finally, several factors have been proposed to mediate the relationship between hearing and cognition, including loneliness and social isolation (Shukla et al., 2020), decreased physical activity (Chen et al., 2015), and frailty (Liljas et al., 2017).

Other pathways have been proposed that more directly explain the relationship between hearing loss and mobility. For example, hearing loss can result in altered spatial awareness, such as the processing of binaural and monoaural cues (Keller et al., 1999). This may in turn reduce one's capacity to perceive and monitor the environment, as well as one's position in the environment (Carpenter & Campos, 2020). Additionally, vestibular dysfunction may underlie the relationship between hearing loss and mobility in older adults. For example, Serrador et al. (2009) demonstrated that decreased otolith function, or the small calcium carbonate crystals in the inner ear that signal to the brain about head position and movement, correlate with increased mediolateral postural sway during standing balance tasks. Indeed, given the similarities across the auditory and vestibular systems, including the mechanisms of functioning and shared inputs to the brain, parallelled pathologies in each system could explain the relationship between hearing loss and mobility decline with age (Carpenter & Campos, 2020).

Interventions. Given the overlap between auditory, cognitive, and motor functioning with age, several interventions have been examined to improve cognition and mobility in older adults with hearing loss. The most common form of treatment for hearing loss is the use of hearing aids, which amplify the auditory signal at differing frequencies to help restore the audibility of sound (Huang & Tang, 2010). Evidence suggests that hearing aid use may improve executive functioning (Sanders et al., 2021; Mansilla-Jara et al., 2025) and balance performance (Borsetto et al., 2021; Ernst et al., 2020; Mahafza et al., 2022), as well as induce neural plasticity (Glick & Sharma, 2020; Karawani et al., 2022). Furthermore, using a longitudinal design, results from a large-scale randomized controlled trial (ACHIEVE) demonstrated that in a subset of participants (i.e., those with cognitive risk factors and lower baseline cognitive scores), the hearing intervention involving audiological counselling and the provision of hearing aids significantly reduced cognitive decline over a three-year period, compared to a health education control (Lin et al., 2023). Auditory training is another rehabilitation strategy that aims to refine the sensory perception of sounds in order to improve speech perception, with results demonstrating increased working memory and overall cognitive performance in adults with hearing loss (Lawrence et al., 2018).

Cognitive interventions have also shown promise in improving cognitive functioning in adults with hearing loss (Lawrence et al., 2018), with some evidence suggesting that older adults with hearing loss benefit more from mnemonic training compared to older adults with normal hearing (Huang et al., 2024). Regarding neural changes, Kawata et al. (2022) demonstrated that in older adults with normal hearing, combined auditory and cognitive training led to volumetric increases in regional grey matter (e.g., dorsolateral PFC, inferior temporal gyrus, cerebellum), while auditory training, alone or in combination with cognitive training, increased functional connectivity in the left temporal pole.

Physical exercise has also shown to improve gait speed and functional mobility in older adults with hearing loss (Jones et al., 2019). Finally, there is some evidence to suggest that combined exercise and cognitive training can improve dual-task working memory performance (Bruce et al., 2019b) and gait speed (Wollesen et al., 2021), as well as functional mobility, global cognitive functioning, and episodic memory (Ozdemir et al., 2024) in older adults with hearing loss. Nevertheless, further research is needed to better understand how hearing ability may moderate training efficacy on cognitive-motor dual-task outcomes.

Current Studies

Taken together, there is now mounting evidence for the increased interdependence amongst cognitive, motor, and auditory functioning in late adulthood. Additionally, cognitive and physical training interventions have been shown to improve cognition and mobility in older adults, with some evidence of improvement in cognitive-motor dual taking in older adults with hearing loss. Nevertheless, several questions remain unanswered. First, it is unclear as to what processes or mechanisms underlie improvements in cognitive-motor dual tasking in older adults following different cognitive and physical training interventions, including physiological, cognitive, and neural adaptations. Similarly, there are limited investigations into whether training induces neuroplastic changes during cognitive-motor dual tasking, and whether this pattern of neural activity reflects increased neural compensation or neural efficiency. Additionally, while there is some evidence for the effect of individual differences factors, such as age, cognitive status, and hearing loss on cognitive-motor dual tasking (e.g., task prioritization, neuroimaging), there is limited research examining the effect of such individual difference factors on training efficacy for dual-task outcomes.

Accordingly, the objectives of the current set of studies were threefold: 1) To investigate the cognitive and physiological mechanisms underlying changes in cognitive-motor dual-task performance following different types of cognitive or physical training interventions in cognitively unimpaired older adults (Study 1), 2) To examine the relationship between neural activity and cognitive-motor dual-task performance before and after executive function training in middle-aged and older adults (Study 2), and 3) To examine the effect of hearing ability on cognitive-motor dual-task performance in MCI participants before and after exercise, alone or in combination, with cognitive training (Study 3). We generally expected independent improvements in cognitive and physical capacities following executive function training and physical exercise interventions, respectively. Additionally, we hypothesized that training would induce neuroplastic changes that would underlie improvements in cognitive-motor dual-task performance. Finally, we expected that individual difference factors, such as poorer hearing ability, older age, and lower baseline cognitive functioning, would be associated with a greater magnitude of improvement in dual-task outcomes following training.

CHAPTER TWO:

Study 1

Multiple Routes to Help you Roam:

A Comparison of Training Interventions to Improve Cognitive-Motor Dual Tasking in Healthy Older Adults

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Manuscript originally published in Frontiers in Aging Neuroscience. I refer to it as Downey et al. 2022 in subsequent manuscripts. Minor changes to formatting and citation style were made to make the manuscript more cohesive with the rest of the dissertation.

Abstract

Cognitive-motor dual tasking is a complex activity that predicts falls risk and cognitive impairment in older adults. Cognitive and physical training can both lead to improvements in dual tasking, however less is known about what mechanisms underlie these changes. To investigate this, thirty-three healthy older adults were randomized to one of three training arms: Executive function (EF; n = 9), Aerobic Exercise (AE; n = 11), Gross Motor Abilities (GMA; n = 13) over 12 weeks (1 hour, 3x / week). Single and dual-task performance (gait speed, m/s; cognitive accuracy, %) was evaluated before and after training, using the 2-back as concurrent cognitive load. Training arms were designed to improve cognitive and motor functioning, through different mechanisms (i.e., executive functioning – EF, cardiorespiratory fitness - CRF, energy cost of walking - ECW). Compared to baseline, we observed few changes in dual-task gait speed following training (small effect). However, dual-task cognitive accuracy improved significantly, becoming facilitated by walking (large effect). There were no differences in the magnitude of improvements across training arms. We also found that older adults with lower cognitive ability (i.e., MoCA score < 26; *n* = 14) improved more on the dual-task cognitive accuracy following training, compared to older adults with higher cognitive ability (i.e., MoCA ≥ 26; *n* = 18). Taken together, the results suggest that regardless of the type of intervention, training appears to strengthen cognitive efficiency during dual tasking, particularly for older adults with lower baseline cognitive status. These gains appear to occur via different mechanisms depending on the form of intervention. Implications of this research are paramount, as we demonstrate multiple routes for improving CMDT in older adults, which may help reduce risk of cognitive impairment.

Key words: aging, executive function, gait, dual-task, exercise, cognitive training

Introduction

Cognitive-motor dual-task performance (e.g., walking while talking) in older adults has been shown to predict future physical and cognitive decline, including mild cognitive impairment and dementia (Montero-Odasso et al., 2012b). Cognitive-motor dual tasking is a multi-faceted behaviour, involving cognitive processes, particularly executive functions (EFs), as well as motor skills. The complex interaction between cognitive and motor domains helps explain why different forms of cognitive or physical interventions have been found to maintain or improve dual-task performance in healthy older adults (Berryman et al., 2014; Fraser et al., 2017; Wollesen & Voelcker-Rehage, 2014). Nevertheless, the potential mechanisms which underlie improvements in dual-task performance across different training modalities are less well-understood. Therefore, the primary aim of this study was to compare the improvements of three different interventions on dual-task performance in healthy older adults and to investigate the mechanisms that could explain these improvements.

As individuals grow older, there is a greater reliance on cognitive resources, particularly EFs, when completing a motor task, such as walking (Hausdorff et al., 2005). This is well-supported by dual-task experiments, wherein dual-task costs (DTCs), or the decrement observed during dual- compared to single-task performance, are found to be greater in older adults compared to younger adults (Li et al., 2001). This decrement in performance has also been shown to occur in older adults at lower levels of cognitive load (e.g., Srygley et al., 2009), and with increased physical task complexity (e.g., usual vs. fast paced walking; Krampe et al., 2011), compared to younger adults. This suggests that with aging, fewer cognitive resources are available to allocate attention to a secondary task. Indeed, neuroimaging evidence shows increased prefrontal cortex activity during dual-task compared to single-task walking, suggesting that more cognitive resources are required for complex gait (Holtzer et al., 2014, Mirelman et al., 2017).

Moreover, according to the posture-first hypothesis, when given instructions to equally prioritize both the motor and cognitive task during dual tasking, older adults prioritize walking, showing greater DTCs in the cognitive domain, while younger adults show more even emphasis across tasks (Li et al., 2001, Verghese et al., 2007). This asymmetry might be due to the greater survival value attributed to walking in old age, thereby leading to greater priority, as compared to the simultaneous cognitive task performance. Together, these findings suggest that age-related declines in cognitive capacity play an increasing role in gait with aging. Interventions aimed at enhancing cognitive capacity in older adults may therefore be critical for improving cognitive-motor dual tasking.

The extant literature suggests that computerized EF training leads to near-transfer effects, such as inhibitory control, divided attention and task-switching (Bherer et al., 2021a; Desjardins-Crepeau et al., 2016) as well as far-transfer effects including dual-task balancing (Li et al., 2010) and walking (Fraser et al., 2017; Smith-Ray et al., 2015; Verghese et al., 2010). Such improvements to motor performance after cognitive training are attributed to the increase in cognitive resources available for dividing one’s attention between the cognitive and motor tasks (Li et al., 2018).

Aerobic exercise (AE) has also been associated with enhanced EF (e.g., inhibition and working memory; Colcombe & Kramer, 2003), brain plasticity (Erickson & Kramer, 2009; Weinstein et al., 2012), and dual-task walking and balance (Fraser et al., 2017). Stillman et al. (2016) propose a conceptual model for possible mechanisms of physical activity in mediating neurocognitive functioning, including cellular and molecular changes, which initiate macroscopic changes to the brain and behaviour, that in turn influence cognition. The cardiovascular hypothesis, which is one component of the model, suggests that aerobic capacity or cardiovascular efficiency may mediate improvements in executive functioning, which could increase cognitive resources required during dual-task processing (Stillman et al., 2016). Indeed, recent research has shown that in older adults, increased cardiorespiratory fitness mediated the improvements seen in processing speed for older-old adults, and task-set costs (i.e., the ability to maintain different response alternatives in memory and prepare to answer multiple tasks) in younger-old adults following AE (Bherer et al., 2021b). Moreover, increased cardiorespiratory fitness may improve dual-task walking performance by decreasing the relative intensity of the walking task for a given gait speed. This in turn may reduce the demands of executive control during dual tasking and allow more attention to be allocated to the cognitive task.

Gross motor abilities training (GMA), also termed *coordination training*, has shown far transfer effects in improving cognitive processes such as executive control and processing speed, as well as decreasing prefrontal activity, suggesting more efficient information processing (Voelcker-Rehage et al., 2011). GMA training has also been shown to improve inhibitory control under single-task conditions (Forte et al., 2013), as well as maximum walking speed under dual-task conditions (Berryman et al., 2014). According to this framework, gait impairments observed in older adults are suggested to be due in part to altered coordination, which increases the amount of energy required to walk due to motor inefficiency (Van Swearingen & Studenski, 2014). Therefore, improvements in dual-task performance following GMA training are suggested to be due to increased coordinated walking abilities, thereby reducing the energy cost of walking (ECW). In turn, this would reduce the relative intensity of the walking task and allow for more resources to be allocated to the cognitive domain. Together, this research suggests that EF, AE, and GMA training have strong potential to improve cognitive-motor dual-task performance, which may be mediated by different underlying mechanisms.

As previously mentioned, comparisons of interventions on cognitive-motor dual-task performance in older adults show similar improvements across groups, providing evidence for a multiple routes perspective. Specifically, Berryman et al. (2014) found similar improvements in cognitive performance during a dual-task condition following either combined resistance with AE training or GMA training. Moreover, in a study contrasting different combinations of active training conditions (EF, AE) and active control conditions (computer lessons, stretching), comparable dual-task improvements were found across the active training groups, including dual-task walking speed, balance (Fraser et al., 2017), and functional mobility (Desjardins-Crepeau et al., 2016). Finally, Pothier et al. (2021) found that global mobility (i.e., Timed up and Go) improved to a similar extent in older adults following either EF, AE, or GMA training. However, no research to date has compared the effect of these three well-established training approaches on cognitive-motor dual-task performance in healthy older adults.

In summary, older adults have poorer dual-task performance compared to younger adults, which is in part due to reduced cognitive resources and motor alterations (Li et al., 2018; Stillman et al., 2016; Van Swearingen & Studenski, 2014). Although there is substantial evidence to suggest that certain interventions may help maintain or improve dual-task performance in older adults, there is limited research directly comparing EF, AE, and GMA training. We therefore sought to investigate the effects of (i) EF (ii) AE and (iii) GMA training on cognitive-motor dual tasking in older adults and to examine the mechanisms underlying each intervention using a proof-of-concept study design.

We hypothesized that: 1) following training, there would be a greater reduction in cognitive dual-task costs (DTCs) compared to gait DTCs. Based upon the posture-first hypothesis, that older adults tend to exhibit greater DTCs to cognitive performance than to walking (Li et al., 2001), there is greater potential for cognitive improvement than motor improvement. We also anticipated that 2) all participants, regardless of the training arm, would have similar improvements in cognitive DTCs following training, based upon previous research findings of null group differences on dual-task costs (i.e., Fraser et al., 2017). In order to verify the intended underlying mechanisms of the interventions, we hypothesized that 3) the different training arms would lead to specific improvements in: i) EF following EF training, ii) cardiorespiratory fitness (i.e., VO_{2peak}) following AE, and iii) ECW following GMA. This hypothesis was grounded in research on the proposed mechanisms of each intervention (Bherer et al., 2021b; Li et al., 2018; Van Swearingen & Studenski, 2014), as well as a joint study from our laboratory that used the same training design, but assessed functioning mobility rather than cognitive-motor dual tasking (Pothier et al., 2021).

Methods

Participants

A total of 125 community-dwelling older adults were first recruited and assessed for eligibility. Thirty participants did not meet inclusion criteria at the time of enrollment, resulting in 95 participants being randomized to each of the three training arms. A total of 17 participants abandoned the intervention voluntarily before its completion (6 from EF: study too demanding = 1, sickness/health issues = 2, no longer interested = 2, too many absences = 1; 6 from AE: study too demanding = 1, sickness/health issues = 2, no longer interested = 3; 5 from GMA: study too demanding = 1, sickness/health issues = 2, no longer interested = 1, involved in another parallel study = 1). Due to data-registration issues concerning the dual-task data for the first six cohorts, we have opted to report only the data for the subsequent cohorts after the problem was addressed. This resulted in a subset of 33 participants (EF = 10, AE = 10, GMA = 13) that were included in the present analyses (see Figure 1 for CONSORT diagram). There were no significant differences between groups in terms of attendance and drop-out rates, suggesting similar adherence across groups. There were also no significant differences in the participant characteristics between participants who had complete data and were analyzed for this study compared to participants who had missing data (see Table 1). Finally, results from Little's MCAR test showed that the data was missing completely at random, $\chi^2(21) = 23.40$, $p = .323$. These findings suggest that the subset of participants is representative of the full dataset and that the data is not biased.

Table 1

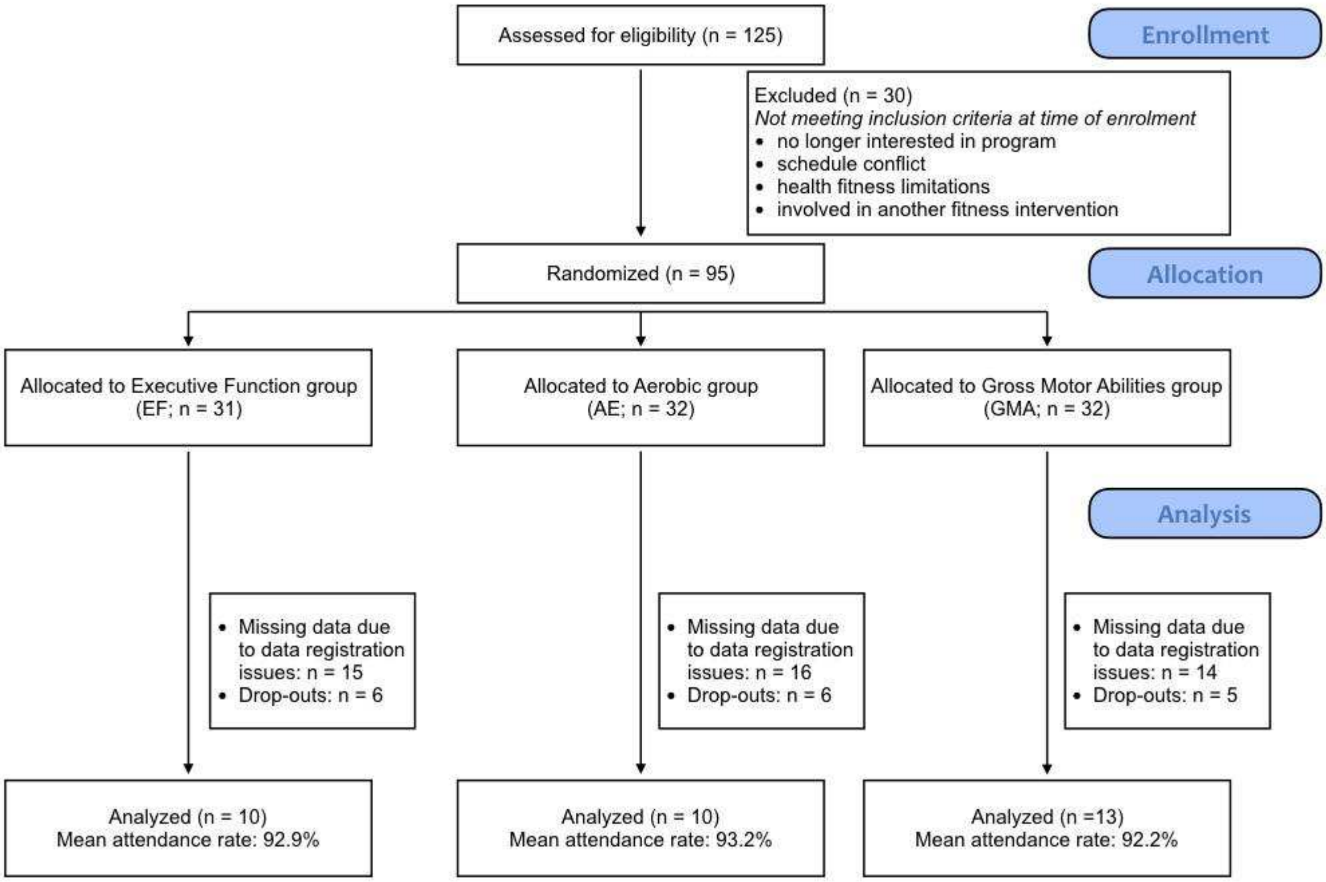
Demographic Information and Baseline Cognitive and Physical Capacity Across Training Groups for Participants Included in the Statistical Analyses and Participants who were not due to Missing Data

	Analyzed data			Missing data		
Characteristic	EF n = 10	AE n = 10	GMA n = 13	EF n = 16	AE n = 14	GMA n = 14
Age (years)	70.0 (6.09)	68.2 (5.34)	70.2 (3.85)	70.4 (5.43)	69.1 (4.49)	70.7 (5.30)
Sex (*n*, % male)	7 (70.0)	(45.5)	5 (38.5)	5 (29.4)	3 (20.0)	5 (31.3)
Education (years)	16.2 (2.70)	18.0 (4.55)	17.4 (5.30)	15.1 (4.31)	15.29 (2.64)	15.0 (2.16)
MoCA	25.4 (2.55)	27.7 (1.89)	25.2 (2.66)	26.4 (2.72)	26.6 (2.59)	26.4 (3.45)
MMSE	28.3 (1.51)	28.5 (1.58)	28.7 (1.21)	28.4 (0.84)	28.7 (1.27)	28.3 (1.50)
TUG (sec.)	9.18 (1.34)	7.79 (1.36)	9.20 (1.40)	9.36 (1.51)	8.80 (1.32)	9.30 (1.86)

Note. MoCA = Montreal Cognitive Assessment, MMSE = Mini Mental State Exam, TUG = Timed Up and Go. Values indicate means and standard deviations in brackets. There were no significant differences across training groups, suggesting that randomization was appropriate. There were no significant differences between participants included in the main statistical analyses and those who were not due to missing data, suggesting that the participant characteristics of the smaller dataset are representative of the full dataset.

Figure 1

CONSORT Flow Diagram



Note. The final row depicts the number of participants included in the study.

A statistical power analysis was performed for sample size estimation, based on published data (Fraser et al., 2017) which compared n-back accuracy and walking speed before and after 12 weeks of different combinations of AE, EF, and placebo controls. The effect sizes for the main effect of Time in this study (n-back accuracy: $n^2 = .11$; walking speed: $n^2 = .29$) are considered to be large using Cohen's criteria (Cohen, 1988). With an alpha set at .05 and power set at 0.95, the projected sample size needed to find a significant main effect of Time with this effect size (G*Power 3.1) is approximately n = 30. Accounting for possible attrition (20%), a total of n = 36 participants is required. Thus, our final sample size of n = 33 is adequate for the main objective of this study. We also provide effect sizes to support the strength of the observed findings. Nevertheless, we recognize that the small sample size due to data registration issues is a limitation of the study.

Eligible participants were 60 years or older, able to speak fluently and comprehend either English or French, and were not on medications that could impair their cognitive and physical test performance. Participants were excluded if they participated in a structured training program over the last year, failed the assessment of readiness to exercise (PAR-Q+; Thomas et al., 1992), or had a chronic medical condition such as cardiopulmonary or musculoskeletal diseases, neurological disease or early signs of dementia (< 26 on the Mini Mental State Exam: MMSE; Folstein et al., 1983), depression (≥ 11 Geriatric Depression Scale; Brink et al., 2013), or major uncorrected perceptual limitations. Participant characteristics by treatment group are shown in Table 1. All participants provided informed consent as approved by the Institut Universitaire Gériatrie de Montreal Ethical Research Committee and Concordia University’s Human Research Ethics Committee.

Procedure

Participants were first screened for eligibility with a phone interview and then a medical evaluation by a geriatrician. Eligible participants completed a pre-test evaluation of cognitive and physical measures, including the dual-task assessment. Participants were then randomized into one of three training protocols: EF, AE, or GMA, which consisted of three, 1-hour sessions a week, for 12 weeks (completed in small groups of 5-8 individuals). Within three weeks after training, participants completed a post-test evaluation using the same measures.

Materials

In addition to the tests described below, other outcome measures (e.g., global mobility, neuropsychological functioning) were administered to the larger sample and are presented elsewhere (Pothier et al., 2021, Vrinceanu et al., 2022).

Background measures. Cognitive functioning was screened using the MMSE (/ 30; Folstein et al., 1983) and Montreal Cognitive Assessment (MoCA; / 30; Nasreddine et al., 2005). While a MoCA score below 26 can be indicative of mild cognitive impairment, participants who scored below this were still included if they performed above the clinical cut-off on the MMSE (i.e., 26). Global mobility was also assessed using the Timed Up and Go (TUG) task (Shumway-Cook et al., 2000).

Primary outcome measures. *Cognitive task.* An auditory 2-back task (Fraser et al., 2017) served as the cognitive outcome measure in single- and dual-task conditions. In the single-task condition, participants performed the 2-back task while standing. In the dual-task condition, they performed the task while walking (see below). Randomly ordered single digits were presented through a set of wireless headphones (Sennheiser Canada, Pointe-Claire, QC, Canada) at a 2-second rate, for a total of 30 seconds. Participants were asked to recall out loud the number they heard two items previously (2-back). The responses were manually recorded during each trial, then converted to accuracy scores (% correct out of 15). *Walking Task.* Participants were instructed to walk around a 23-meter oval track, demarcated by a single stretch of tape on the floor, at their normal walking speed. Each walking trial was initiated by the audio signal, “GO”, heard through wireless headphones, and ended with the audio signal, “STOP”. Each trial lasted 30 seconds. The distance walked was manually recorded and divided by 30 seconds to attain a measure of gait speed (m/s). *Dual-Task.* Participants completed the 2-back cognitive task while concurrently walking at a self-selected pace. They were instructed to perform both the cognitive and walking task equally well.

Participants were first familiarized with each of the single tasks before introducing the dual-task procedure. Feedback on performance was only given during the familiarization portion of the task. Each block consisted of three trials (single-task 2-back, single-task walk, and dual-task), which were repeated across four blocks. Dual-task costs (DTC; %) were calculated as: [(single-task – dual-task) / single task * 100], for cognitive accuracy (i.e., cognitive DTCs) and gait speed (i.e., walking DTCs; greater positive number indicates poorer performance when completing the dual-task compared to single-task). DTC change scores were calculated by subtracting the post-training DTCs from the pre-training DTCs (greater negative number indicates more improvement following training).

Secondary outcome measures. In addition to the primary experimental outcomes, three indexes were included to address the underlying mechanisms associated with each training type and assessed during pre- and post-training phases so that the *magnitude of change* in executive function, aerobic capacity, and motor skills could be quantified and considered as potential predictors of change in dual-task walking.

Changes in executive function. Changes in executive functions due to training were measured using a variant of the Stroop task used during training. Instead of using letters, the pre- and post-intervention variant involved digits. The assessment comprised of five different conditions (familiarization, reading, counting, inhibition, switching); however, reaction times for the inhibition and switching trials were analyzed as potential mechanisms underlying the EF training as these tasks rely most heavily on executive function. In the inhibition condition, digits were presented on the screen, whereby the number of digits was incongruent with the digit displayed (e.g., five number twos were presented). Participants were instructed to identify the quantity of digits presented, while inhibiting responses indicating the digits that were displayed on the screen. In the switching condition, the stimuli were identical to those in the inhibition condition, except that on some trials, the digits were surrounded by a white frame, to indicate a goal switch, whereby participants had to identify the digit that was presented on the screen, rather than indicating the quantity of digits.

Changes in cardiorespiratory fitness. The proposed mechanism thought to underlie the AE training protocol was cardiorespiratory fitness, as measured by peak oxygen uptake (VO_{2peak}). The detailed protocol has been described previously (Berryman et al., 2012). Briefly, participants wore an electrocardiogram to monitor heart rate and a mask to measure gas exchange during a maximal graded exercise test on a cycle ergometer. The test began at a pre-defined load and then increased in workload by 15 Watts. Testing was completed when participants reached exhaustion (i.e., were unable to maintain the cadence of 60 to 80 revolutions per minute) or according to reasons described by the American College of Sports Medicine (ACSM, 2012). VO_{2Peak} was defined as the highest volume of oxygen consumed over a 30 second interval in $ml.kg^{-1}.min^{-1}$.

Change in the energy cost of walking. The mechanism thought to underlie the GMA training protocol is the energy cost of walking (ECW). All participants were equipped with the same mask to measure the O_2 consumption and CO_2 production as during the VO_{2Peak} assessment. However, participants walked on the treadmill during 6 minutes at a constant speed of 4 $km.h^{-1}$. The oxygen cost of walking (OCW), in $ml.kg^{-1}.min^{-1}$, represents the mean VO_2 from the last two minutes of the walking task. The ECW was calculated as described elsewhere (Berryman et al., 2012). Briefly, the gross OCW ($ml.kg^{-1}.min^{-1}$) was divided by the walking speed ($m.min^{-1}$) to obtain a value in $ml.kg^{-1}.m^{-1}$. Thereafter, values in $ml.kg^{-1}.m^{-1}$ were first converted in $L.kg^{-1}.m^{-1}$. Using the respiratory exchange ratio (RER) corresponding to the last 2 minutes of walking, an appropriate energy equivalent of oxygen ($J.L^{-1}$) was used to convert the previously calculated ECW ($L.kg^{-1}.m^{-1}$) in $J.kg^{-1}.m^{-1}$. RER had to be below 1 during the last two minutes of walking so that oxygen values could be considered for further analyses. These procedures are in agreement with the scientific literature for moderate intensity exercise (Fletcher et al., 2009; Xu & Rhodes, 1999).

Training Protocol

Executive function training. The EF intervention was completed on individual tablets while seated. Participants completed three executive function tasks per session: (i) visual n-back, (ii) Stroop, and (iii) dual-task (20 minutes / task).

The n-back task was designed to improve updating. Participants were required to indicate whether the current number presented matched the number from *n steps* earlier in the sequence (Kirchner, 1958). The stimuli included numbers between “1” to “9”. Reaction times (ms) and accuracy (total number correct/maximum possible correct) were recorded. Difficulty levels were incremented over the three months of training (from 1-back to 3-back).

The modified Stroop task was designed to improve inhibition and switching and was comprised of five different conditions (familiarization, reading, counting, inhibition, switching). In the familiarization condition, participants were required to press a button corresponding to the digit presented on the screen (“1” to “3” with their left thumb, “4” to “6” with their right thumb). In the reading condition, multiple identical digits were presented in a small group, where the identity of the digit corresponded with the quantity of the digits presented (e. g., four copies of the digit “4”) and participants had to press the corresponding button with their thumb. In the counting condition, groups of one to six asterisks were presented and the participants had to report how many asterisks were present. In the inhibition condition, letters were presented in small identical groups, however the letters presented were incongruent with the larger letter that was formed (e.g., copies of small letters “L” to form a big "H"). Participants were instructed to identify the larger formed letter, while avoiding responses to the small grouped letters. In the switching condition, the stimuli were identical to those in the inhibition condition, except that on some trials, the group of small letters was surrounded by a white frame, to indicate a goal switch, whereby participants had to identify the small letters instead of the bigger formed letter for those trials only.

The dual-task program was designed to improve divided attention by having participants perform two discrimination tasks either alone or simultaneously. Stimuli were presented either visually (e.g. fruits vs. modes of transport; letters vs. numbers) or orally (sounds vs. beeps) using headphones. Participants completed blocks of single-task trials (Pure blocks) or mixed trials that randomly involved one or both tasks (Single-mixed trials and Dual-mixed trials, respectively). For Dual-mixed trials, participants were instructed to respond to both stimuli equally. However, after two training sessions, participants were encouraged to prioritize one hand over the other to increase the level of difficulty (i.e., in the dual-mixed trials when two stimuli were presented, participants were asked to make a response using their left or right hand first before making a response with the other hand).

Aerobic exercise training. The AE training involved recumbent cycling designed to enhance cardiorespiratory fitness and aerobic endurance. Each training session alternated between high intensity interval exercises and moderate intensity continuous exercises. Such a program was previously implemented and led to significant improvements in cardiorespiratory fitness (Berryman et al., 2014). Maximal Aerobic Power (MAP) was measured at baseline and represents the highest mechanical power output (Watts) produced by participants at the end of a maximal graded test performed on a cycle ergometer (Lode, CORIVAL). Participants began at a pre-defined starting workload for women (35 Watts) and men (50 Watts). The workload then increased by 15 Watts until exhaustion. Participants were required to maintain a pedaling rate of 60 to 80 revolutions per minute. Testing was completed when participants were unable to maintain the cadence or according to reasons described by the American College of Sports Medicine (ACSM, 2012). This information was used to calibrate individualized workload for the AE training.

Each training session included a 10-minute warm-up, during which participants maintained 50% of their MAP. For the HIIT sessions, the warmup was followed by two 5-minute intervals, during which participants alternated between 15 second bouts of cycling at 100% MAP, with recovery at 60% MAP. For the continuous low intensity training, the warmup was followed by 20 minutes of cycling at 65% MAP. Every session ended with a 10-minute cool-down period at 50% of their MAP. The intensity of the continuous aerobic exercise was increased individually according to each participant’s MAP by 5% after each month, with all participants increasing to 75% MAP at the end of training for the continuous low intensity training and 110% MAP for the HIIT training.

Gross motor abilities training. The GMA training protocol was adapted from a previous study (see Berryman et al., 2014 for detailed protocol). Briefly, participants started each session with a low-intensity walking exercise on a treadmill at a self-selected pace for ten minutes (max. 2.5 km/h, 1% incline). Participants then completed different exercises designed to improve coordination, balance and agility for approximately 30 minutes (e.g., walking over obstacles, standing on one foot, juggling lessons). As the intervention progressed, exercises combining multiple skills (coordination, agility, balance) were added to increase the level of difficulty (e.g., maintaining balance on one foot and throwing a ball in a box). Participants then completed another ten minutes of low intensity walking on a treadmill. Each session concluded with five minutes of stretching and relaxation exercises.

Statistical Analyses

All data analyses were completed using IBM SPSS Statistical Software version 26. The data were screened for normality, outliers, and missing values. To evaluate the effectiveness of randomization to groups, one-way ANOVAs were carried out using each of the background measures and key outcome measures (single- and dual-task gait speed and 2-back accuracy) collected prior to the training phase. To evaluate the dual-task manipulation at baseline, paired sample t-tests were carried out on single- and dual-task gait speed and cognitive accuracy using the pre-training assessment data.

Two 2 × 3 Mixed Factorial ANOVAs were then conducted on each of the DTC scores (Cognitive, Walking) to assess change from pre- to post-training across training arms, where the within-subjects effect was Time (pre- vs. post-training) and the between-subjects effect was

Training Group (EF, AE, GMA). A set of 2 x 3 ANOVAs were then conducted for each of the potential mechanisms underlying the training arms (Stroop inhibition and switching RT, CRF, ECW) to assess the within-subjects effect of Time (pre- vs. post-training) and the between-subjects effect of Training Group (EF, AE, GMA). All follow-up analyses were Bonferroni corrected. In order to ensure that the results were not influenced by regression to the mean, all significant ANOVAs were followed up with an ANCOVA, where the covariate was the baseline score on the outcome measure found to be significant. Effect sizes were calculated as Hedges' *g* for the t-tests and ANOVAs to account for small sample size, with the magnitude of effect being considered small ($.2 < ES \leq .5$), moderate ($.5 < ES \leq .8$), or large ($ES > .8$).

Results

Baseline Group Differences

Results revealed no significant differences (*p*s > .05) between groups for any of the background measures (i.e., age, sex, education, MoCA, MMSE, TUG) or key experimental measures in the pre-training phase, suggesting that randomization was effective (Table 1).

Baseline Single- and Dual-Task Performance

No significant differences between single- and dual-task conditions were found in performance on cognitive accuracy ($t(32) = 1.58$, $p = .123$), or gait speed ($t(32) = .66$, $p = .514$) at baseline. While not significant, it is notable that the range of scores was quite large, particularly for the single-task ($SD = 19.49\%$) and dual-task ($SD = 18.90\%$) cognitive accuracy data.

To understand the large range of cognitive task performance, we examined global cognitive status as an individual differences factor as a possible influence. Specifically, we conducted two *post-hoc* One-Way ANOVAs on single- and dual-task cognitive accuracy scores, splitting participants between low (i.e., MoCA score < 26; $n = 14$) or high cognitive status (i.e., MoCA ≥

26; *n* = 18). Results showed that participants with lower MoCA scores at baseline had significantly lower cognitive accuracy under single- (*F*(1, 31) = 10.8, *p* = .003) and dual-task conditions (*F*(1, 31) = 10.9, *p* = .002), compared to participants with higher MoCA scores. Notably, there were no significant age differences between low versus high MoCA scorers.

Training Effects

Regarding walking DTCs, there was no significant effect of Time, *F*(1, 30) = .618, *p* = .438, *g* = -.11), with DTC scores remaining similar following training (*M* = - 0.16*%)* compared to baseline (*M* = 0.92*%)*. There was also no significant effect of Group (*p* = .406*),* nor a significant Time by Training Group interaction (*p* = .369; Table 2).

For the cognitive DTCs, there was a significant main effect of Time, *F*(1, 30) = 8.82, *p* = .006, *g*: - .83 (large effect size; Figure 2), indicating diminished DTCs following training, such that dual tasking became facilitative after training (*M* = - 8.03%), compared to baseline, (*M* = 3.89%). There was also a significant main effect of Training Group, *F*(2, 30) = 4.36, *p* = .022, irrespective of Time. Follow-up pairwise comparisons revealed that the GMA group had significantly lower cognitive DTCs (*M* = - 8.22%) compared to the AE group (*M* = 2.96%), *p* = .032. However, there was no significant interaction effect of Time and Training Group (*p* = .845; Table 2), suggesting that all groups improved similarly. Indeed, a follow-up One Way ANOVA comparing the change in cognitive DTCs from pre- to post-training across groups was non-significant (*p* = .943), and effect sizes showed similar rates of improvements across groups (*g:* EF: -.91 [large effect], AE: -.65 [moderate effect], GMA: -.76 [moderate effect]). Results from the ANCOVA, where the between-subjects factor was Training Group and the covariate was baseline cognitive DTC scores, showed similar findings as our primary analysis, such that that the cognitive DTC change scores did not significantly differ across groups, $F(2, 29) = 2.46$, $p = .104$, suggesting that the results are not due to a regression to the mean.

Table 2

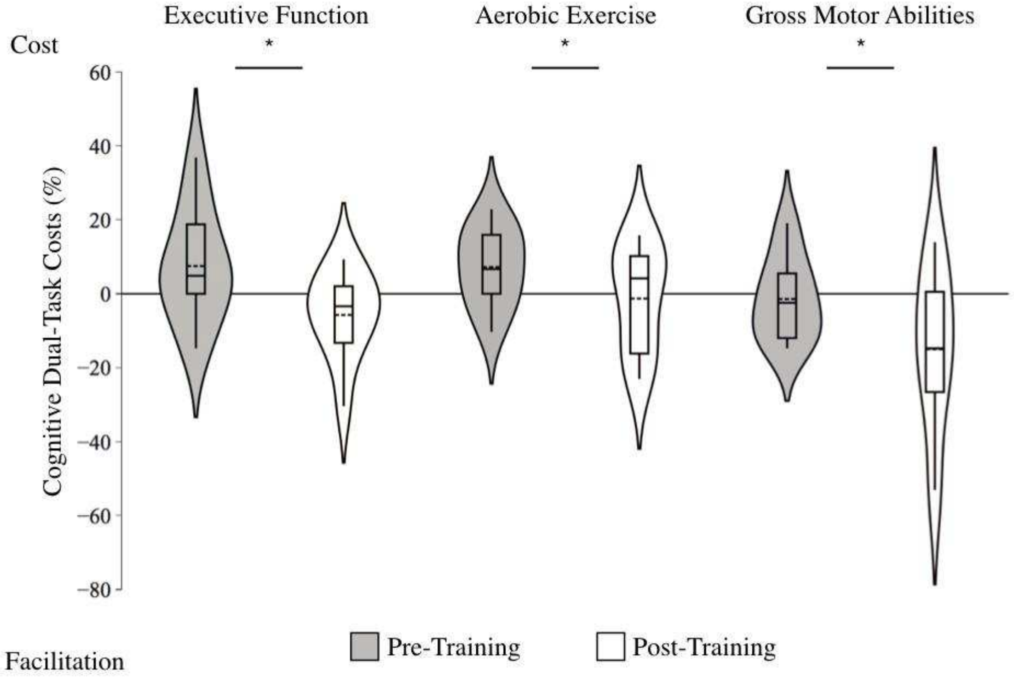
Dual-Task Costs Before and After Training Across Groups

		Cognitive DTC (%)			Walking DTC (%)		
		Mean (SD)	*F*	*p*	Mean (SD)	*F*	*p*
Between-subjects effects							
Group	EF	0.90 (9.77)	4.36	0.022*	-2.29 (7.41)	0.928	0.406
	AE	2.96 (9.77)			1.62 (7.41)		
	GMA	-8.22 (9.77)			1.47 (7.41)		
Within-subjects effects							
Time	Pre-training	3.89 (12.8)	8.82	0.006*	0.917 (7.45)	0.618	0.438
	Post-training	-8.03 (17.5)			-0.16 (10.1)		
Time x Group	EF Pre-training	7.49 (15.5)	0.169	0.845	-1.38 (8.18)	0.911	0.369
	EF Post-training	-5.70 (11.7)			-3.20 (9.55)		
	AE Pre-training	7.19 (10.5)			3.53 (8.36)		
	AE Post-training	-1.27 (14.1)			-0.30 (11.0)		
	GMA Pre-training	-1.41 (11.2)			0.67 (5.95)		
	GMA Post-training	-15.0 (21.8)			2.27 (9.90)		

Note: DTC = dual-task cost as derived by [(ST – DT)/ ST] * 100; EF = executive function training; AE = aerobic exercise; GMA = gross motor abilities training; There was a significant reduction in cognitive DTCs following training (negative score indicates dual-task facilitation, such that cognitive accuracy was better during dual tasking, compared to single-tasking), with no significant change in walking DTCs following training.

Figure 2

Violin Plot of Cognitive Dual-Task Costs Before and After Training Across Training Groups



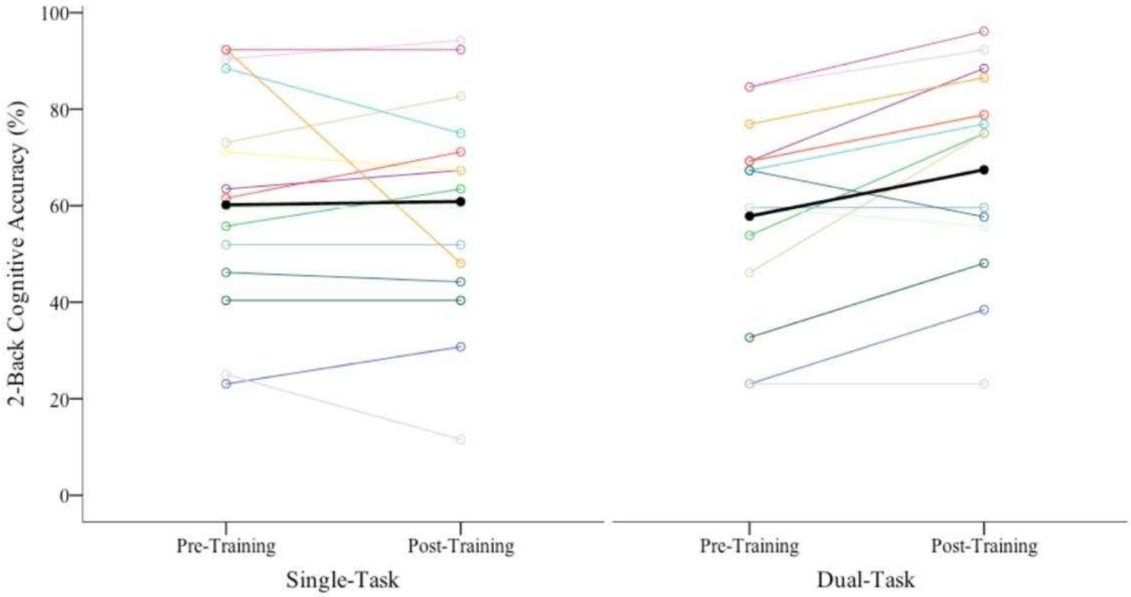
Note. Positive scores indicate greater dual-task costs (i.e., lower 2-back accuracy during dual tasking compared to single-tasking), whereas negative scores indicate dual-task facilitation (i.e., higher 2-back accuracy during dual-task compared to single-task). The length of each curve represents the range of scores, the width represents the frequency of data points in each region, and the darkened line within each curve represents the median. Following training, cognitive accuracy dual-task costs improved, regardless of the training protocol (*g* = - .83).

Given the unusual finding that the cognitive accuracy DTCs became better during walking (dual-task facilitation) after training, we sought to better understand this effect using *post-hoc* individual differences analyses. As mentioned, there was large variability in 2-back performance that was influenced by baseline cognitive status as measured with the MoCA. Therefore, we compared post-training cognitive DTCs across those with low (i.e., MoCA score < 26, *n* = 14) versus high cognitive status (i.e., MoCA ≥ 26, *n* = 18) using a One-Way ANOVA. Results showed a significant difference between groups, such that low MoCA scorers at baseline were more likely to have a dual-task facilitative effect post-training (*M* = - 14.9, *SD* = 16.9), compared to high MoCA scorers, who showed negligible dual-task costs post-training (*M* = -0.17, *SD* = 11.7), *F* (1, 31) = 8.52, *p* = .007 (see Figure 3 for single- and dual-task scores before and after training between low vs. high MoCA scorers). To further investigate if this result was due to a regression to the mean, we conducted an ANCOVA, where the between-subjects factor was MoCA status (i.e., low vs. high scorers) and the covariate was baseline cognitive DTC scores. Results showed similar results to our initial One-Way ANOVA, such that the cognitive DTC change scores were significantly greater in the low MoCA scorers compared to the high MoCA scorers, F(1, 29) = 5.303, *p* =.029, suggesting that the results are not significantly influenced by regression to the mean.

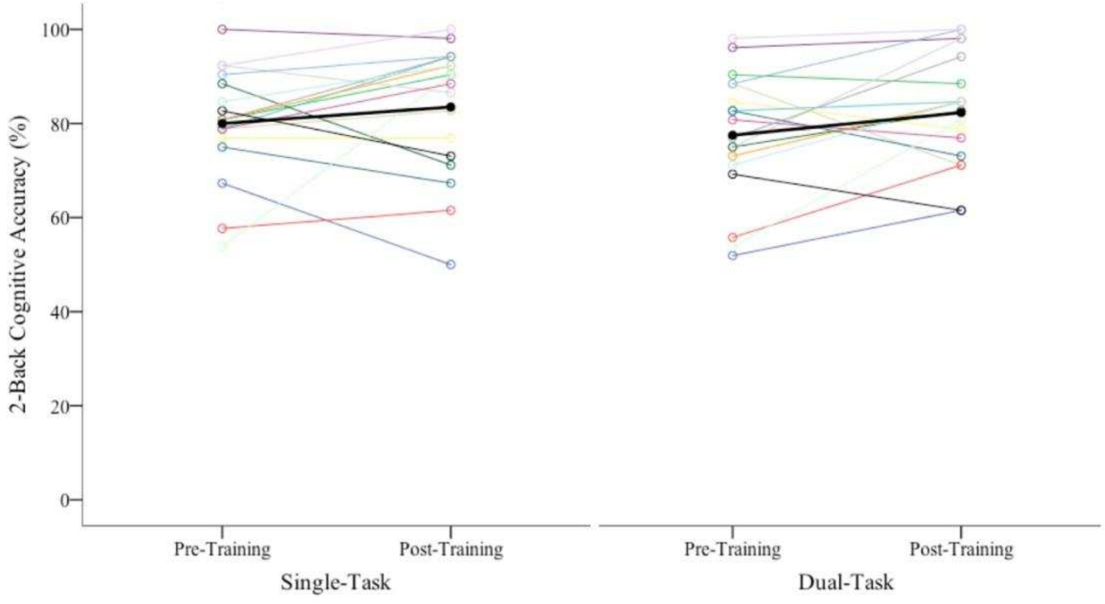
Given the cognitive accuracy dual-task facilitation following training, we wondered whether attentional allocation to the walking task differed across participants with low versus high cognitive status. Results from the *post-hoc* One-Way ANOVA showed no significant differences in post-training walking DTCs between participants with low (*M* = 3.16 *SD* = 9.98) versus high baseline cognitive status (*M* = -2.87, *SD* = 9.88), *F* (1, 31) = 2.91, *p* = .10.

Figure 3

Single- and Dual-Task Cognitive Accuracy Performance Before and After Training Across Participants with Low Versus High MoCA Scores



A. **Low MoCA Scorers**



B. **High MoCA Scorers**

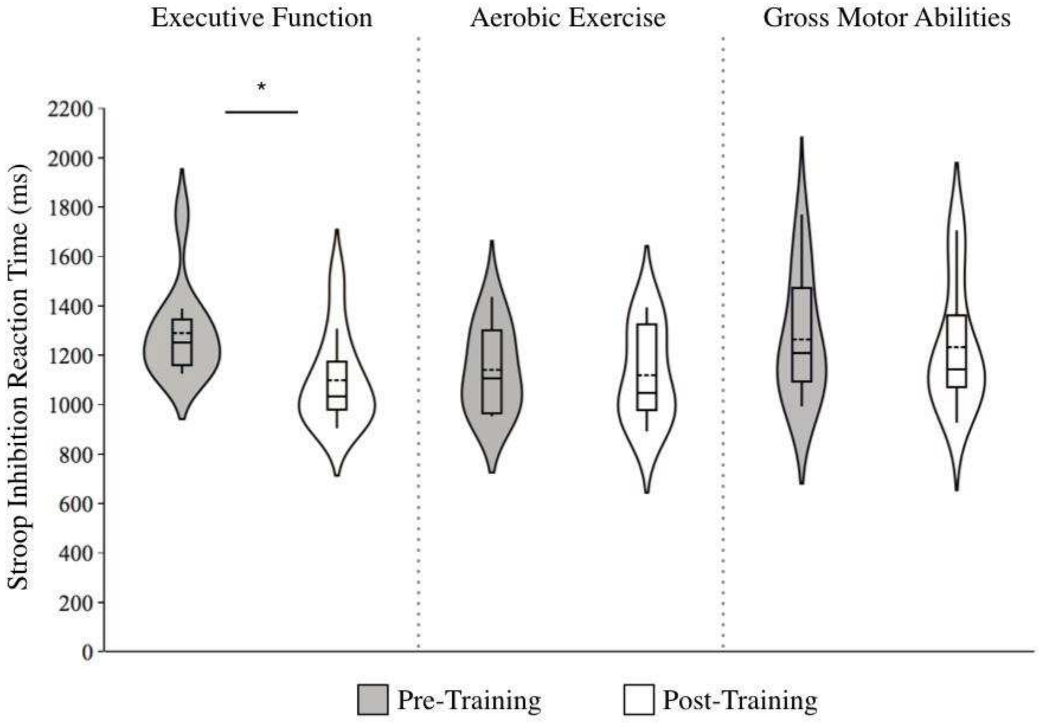
Note. **A.** Low baseline MoCA scorers (i.e., < 26; n = 14), **B.** High baseline MoCA scorers (i.e., ≥ 26; n = 18). Each line represents an individual participant score (black lines indicate the mean). While the high MoCA scorers have the highest accuracy before and after training, there is greater improvement in the single to dual-task cost ratio in low MoCA scorers, leading to dual-task facilitation.

Mechanisms Underlying Dual-Task Improvements

Executive function. A significant effect of Time, F (1, 30) = 30.3, $p < .001$, and a Group by Time interaction, F (2, 30) = 13.2, $p = .001$, was found for the Stroop inhibition condition, with reaction times only decreasing for the EF group; g: EF = -0.96 [large effect] $\Delta = -14.8\%$; AE = -0.11 [no effect], $\Delta = -1.90\%$; GMA = -.12 [no effect], $\Delta = -2.49\%$; Figure 4. Similarly, in the switching condition, there was a significant effect of Time (F (1, 30) = 23.4, $p < .001$), as well as a Group by Time interaction, F (2, 30) = 13.5, p < .001, whereby only the EF group showed improvement, F (1, 25) = 9.18, $p < .01$; g: EF = -1.59 [large effect], $\Delta = -25.8\%$; AE = -.05 [no effect], $\Delta = -0.98\%$; GMA = -0.25 [small effect], $\Delta = -4.30\%$; Figure 5.

Figure 4

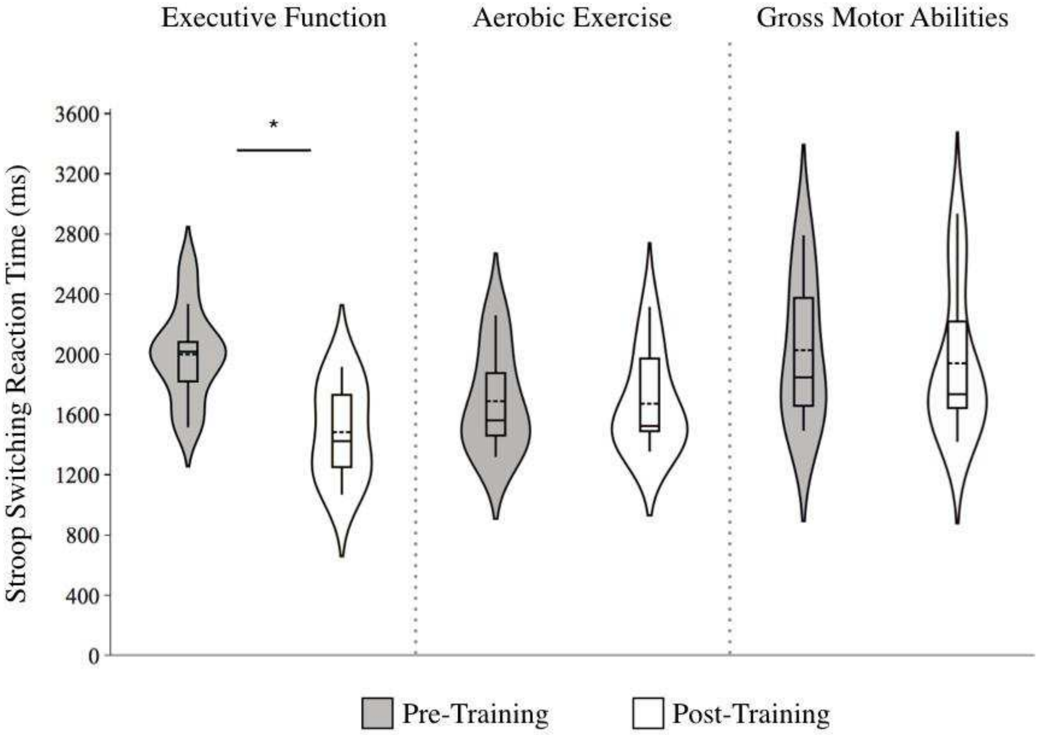
Violin Plots of Stroop Inhibition Reaction Times Before and After Training Across Training Groups



Note. Lower scores indicate faster responses. The length of each curve represents the range of scores, the width represents the frequency of data points in each region, the solid line within each boxplot represents the median, and the dotted line represent the mean. There were significant improvements in reaction time for the executive function training group alone (g = - .96 [large effect], $\Delta = -14.8\%$).

Figure 5

Violin Plots of Stroop Switching Reaction Times Before and After Training Across Training Groups

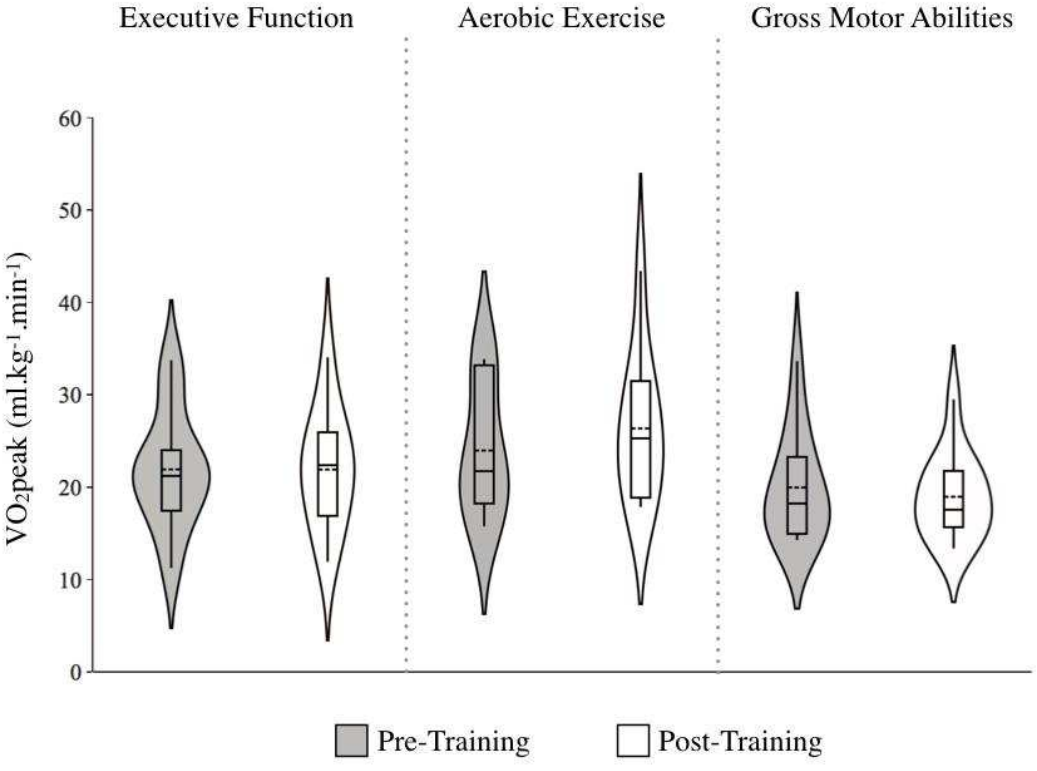


Note. Lower scores indicate faster responses. The length of each curve represents the range of scores, the width represents the frequency of data points in each region, the solid line within each boxplot represents the median, and the dotted line represent the mean. There were significant improvements in reaction time for the executive function training group alone (*g* = -1.59 [large effect], Δ = -25.8%).

Cardiorespiratory fitness. There was no significant effect of Time, *F* (1, 30) = 1.94, *p* = .174, though there was a Group by Time interaction that approached significance, *F* (2, 30) = 3.23, *p* = .054. A post hoc One Way ANOVA comparing the change in VO_{2Peak} across training groups was significant, F (2, 30) = 3.70, *p* = .037, with the AE group improving the most; AE: *g* = 0.31 [small effect] Δ = 9.07%; EF: *g* = -0.001 [no effect], Δ = -0.05%; GMA: *g* = -.07 [no effect], Δ = -1.98%; Figure 6. Also notable is how the AE group had the highest baseline VO_{2peak} (*M* = 24.0, *SD* = 7.10), compared to EF (*M* = 21.9, *SD* = 6.48) and GMA (*M* = 19.9, *SD* = 5.84).

Figure 6

Marker of Cardiorespiratory Fitness (i.e., VO_{2Peak}) Before and After Training Across Training Groups

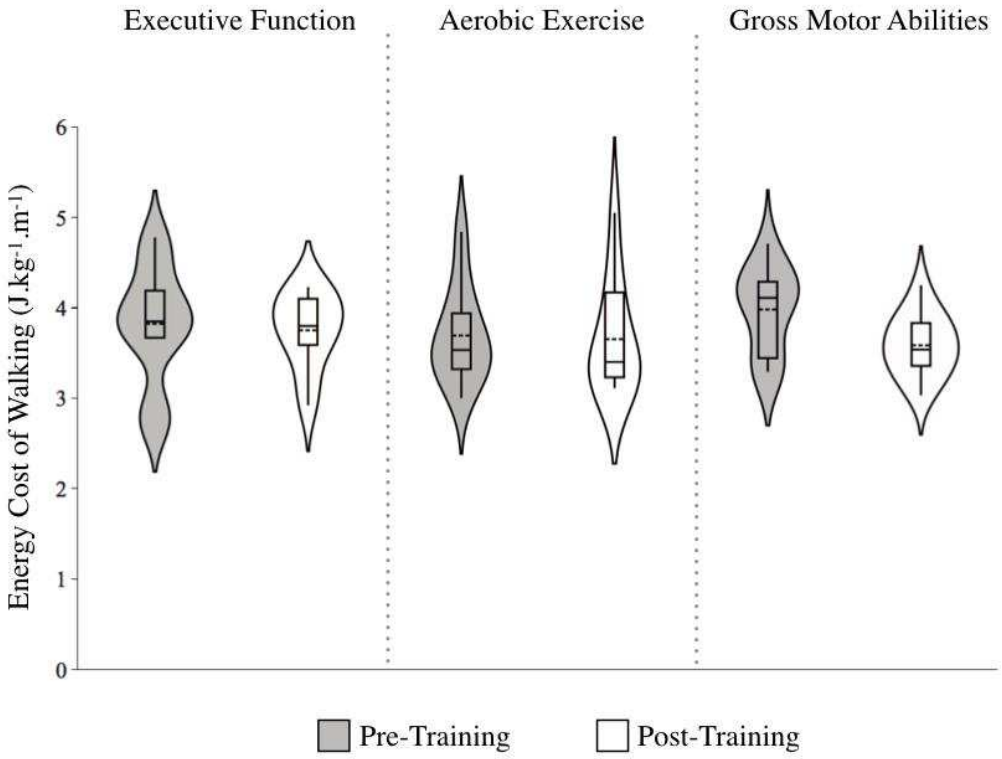


Note. Higher scores indicate better cardiorespiratory fitness. The length of each curve represents the range of scores, the width represents the frequency of data points in each region, the solid line within each boxplot represents the median, and the dotted line represent the mean. While VO_{2Peak} improved following aerobic exercise training (*g* = 0.31 [small effect] Δ = 9.07%;), the interaction effect only approached significant. As the aerobic exercise group had the highest VO_{2peak} levels at baseline, this may have limited the possibility for further improvement through training.

Energy cost of walking. There was a main effect of Time that approached significance, *F* (1, 30) = 3.85, *p* = .059, with ECW decreasing following training. There was no significant Group by Time interaction, *F* (2, 30) = 1.86, *p* = .175. However, the ECW was found to decrease the most in the GMA group: *g*: GMA = -0.94 [large effect], Δ = -11.0%; EF = -0.13 [no effect], Δ = -1.93%; AE = -0.07 [no effect], Δ = -1.15%; Figure 7.

Figure 7

Energy Cost of Walking (ECW) Before and After Training Across Training Groups



Note. Lower scores indicate more efficient walking. The length of each curve represents the range of scores, the width represents the frequency of data points in each region, the solid line within each boxplot represents the median, and the dotted line represent the mean. Improvements in ECW were found following gross motor abilities training (*g* = - .94 [large effect] Δ = -11.0%), although the interaction effect was not significant.

Discussion

We aimed to evaluate the effect of cognitive training, aerobic exercise, and gross motor training on cognitive accuracy and gait speed under single- and dual-task conditions in healthy older adults. Notably, compared to pre-training levels, cognitive DTCs improved, switching to dual-task facilitation, regardless of the training modality (i.e., similar magnitudes of improvement following either cognitive or physical interventions), whereas no training effects were observed in gait speed DTCs. To better understand how various interventions have led to similar improvements in dual-task performance, we also investigated potential mechanisms specific to each training protocol. We found significant improvements in EF for participants in the cognitive training group alone, as well as larger improvements in cardiorespiratory fitness for participants in the aerobic exercise group, and greater reductions in metabolic energy demands of walking for participants in the gross motor training group. These findings are consistent with a recent study from our laboratory which had a larger sample size, showing comparable improvements in global mobility following the three interventions (Pothier et al., 2021).

Greater Improvements in Cognitive vs. Gait DTCs

The finding of greater improvements in cognitive DTCs compared to gait DTCs following training is consistent with our first hypothesis, which was based upon the postural prioritization hypothesis (Li et al., 2001). Specifically, since older adults tend to prioritize walking performance over cognitive accuracy during dual tasking due to its heightened survival value, we expected there would be a greater opportunity for improvement in cognitive DTCs. Very notably, the improvements in cognitive DTCs became facilitative, meaning that cognitive accuracy became better while walking compared to while standing. However, this did not come at a decrement to gait performance.

To better understand the dual-task facilitative effect, *post-hoc* analyses were conducted, comparing dual-task performance across participants with varying levels of cognitive ability, as measured by the MoCA. First, we demonstrated that older adults with lower MoCA scores (i.e., < 26 – the clinical cut-off for mild cognitive impairment), had poorer baseline 2-back accuracy under both single and dual-task conditions. While this was expected, we did not anticipate our next finding, which was that post-training, participants with low baseline cognitive status had cognitive dual-task facilitation, whereas participants with high baseline cognitive status scores had negligible dual-task costs.

We had instead expected that older adults with high MoCA scores might have few DTCs at baseline and would be more likely to show dual-task facilitation post-training, whereas older adults with low MoCA scores might have greater costs at baseline, which would become negligible post-training. This expectation was based upon research by Wollesen & Voelcker-Rehage (2019), who demonstrated that older adults with greater physical functioning (i.e., handgrip strength) had faster gait speed. Moreover, in the cognitive literature, mnemonic training has been shown to magnify individual differences based on age and baseline performance. Specifically, younger participants and those with higher baseline performance tend to have greater mnemonic gains following training (Baltes, 1987; Lövden et al., 2012).

Although in our study participants with higher baseline MoCA scores did not have the facilitative effect as predicted, we did show that they had negligible DTCs both before and after training, which may suggest efficient complex walking behaviour. For participants with lower cognitive status at baseline, an increase in cognitive resources following the intervention may have allowed greater attentional allocation to the cognitive task, leading to dual-task facilitation, while maintaining walking performance. The observed dual-task facilitation in cognitive accuracy thus appears to be driven by the proportion of older adults with lower cognitive status. This finding has direct clinical implications for older adults with low cognitive status as it demonstrates that either cognitive or physical interventions can improve cognitive efficiency during complex walking, which may reduce risk of falling and cognitive decline.

One important limitation to consider when interpreting these results is the lack of a control group, which makes it difficult to conclude whether the improvements observed in cognitive DTCs were not solely due to re-test effects. As this study followed a proof of concept design, the aim was to directly compare three well-established intervention protocols that have shown to be effective in improving cognitive or motor functioning in older adults. Indeed, EF and AE training have been shown to lead to greater improvements in executive functioning (e.g., DTCs on a computerized divided attention task, Stroop switching reaction time) compared to a placebo control group (Bherer et al., 2021a; Desjardins-Crepeu et al., 2016; Fraser et al., 2017). Single- and dual-task walking speed have also been shown to improve more following EF training compared to a wait-list control group (Verghese et al., 2010). GMA training has also been shown to improve executive control and processing speed more than a placebo control group (Voelcker-Rehage et al., 2011). These studies highlight the effectiveness of the chosen interventions for the current study, and while the current design does not deter from the possibility of re-test effects, the evidence suggests that the interventions are effective in improving cognitive or motor functioning, which may be applied when interpreting the current study findings. Additionally, an analysis to control for regression to the mean, which included baseline cognitive DTC performance as a covariate, showed similar results as our post hoc analysis comparing low versus high MoCA scorers, such that there was greater improvement in cognitive DTCs in the participants with low baseline MoCA performance compared to high baseline MoCA performance. This finding suggests that our results remain significant even after controlling for regression to the mean.

Another important note to consider is that characteristics such as age and baseline neuropsychological performance may impact practice effects, with researchers showing that there are smaller practice effects in older adults compared to younger adults, as well as older adults who have poorer memory performance (Calamia et al., 2012). Given that the dual-task facilitation effect following training was primarily driven by older adults with low MoCA scores, we believe that more than 12 weeks between the pre- and post-training assessments was sufficient to reduce practice effects in this population. Nevertheless, without a control group, it is not possible to conclude whether the improvements in dual-task cognitive accuracy were not due to re-test effects, so the results should be interpreted with this in mind.

Comparable Improvement in Dual-Task Performance Across Training Modalities

The finding that cognitive DTCs improved regardless of training modality is consistent with our second hypothesis. While our small sample size may have left the interaction analyses underpowered, we included effect sizes to aid in interpreting our results. The effect sizes suggest similar improvement across training modalities, with the executive function training having a large effect size, and the aerobic exercise and gross motor training having moderate effect sizes. Analyses including baseline cognitive DTC scores as a covariate showed similar findings of null group differences, suggesting that the level of improvements observed across each training group were not solely due to a regression to the mean. Moreover, in a joint study involving the same training design and participants as the current study, but with a larger sample size (i.e., n = 78; Pothier et al., 2021), results show similar improvements in TUG walking speed regardless of training modality. We found consistent results in TUG improvements in the current sub-sample of 33 participants, suggesting that the training effects are representative of the full dataset. As such, while the small sample size is an important limitation to consider, we provide moderate evidence that may suggest similar improvements in cognitive DTCs across training modalities. Importantly, our findings are consistent with a number of other studies which have revealed comparable improvements in dual-task walking speed and balancing (Fraser et al., 2017), as well as functional mobility (Pothier et al., 2021) following different combinations of cognitive and aerobic exercise training. Our findings are also in line with research demonstrating similar improvements in single- and dual-task cognitive performance following either combined high-intensity aerobic and strength training or gross motor activities (Berryman et al., 2014).

Together, our research contributes to the growing view that multiple types of interventions may be beneficial for maintaining cognitive and motor functioning in older adults. Future preference clinical trial designs may test whether having the option to participate in either cognitive or physical training might promote sustained adherence to training or could lead to increased self-efficacy in the context of cognitive-motor dual-task outcomes.

Mechanisms Underlying Dual-Task Improvements

Given the apparent multiple routes perspective, our final aim was to better understand *how* these various interventions lead to similar improvements in dual-task performance. Executive function performance was only found to improve following the cognitive intervention, as demonstrated by reduced response times on the Stroop inhibition and switching conditions. By increasing cognitive capacity, additional resources may have been allocated to the cognitive task while dual tasking, thereby improving performance (Li et al., 2018). Additionally, the energy demands associated with walking were found to specifically improve following gross motor activities. By increasing gait coordination and subsequently reducing the amount of energy needed to walk, dual tasking may have been less demanding as it would require fewer physical and cognitive resources (Van Swearingen & Studenski, 2014). Finally, we hypothesized that cardiorespiratory fitness would improve the most following aerobic exercise, however the effect size to support this was small. While the statistical testing approached significance, our results showed a 9% increase in cardiorespiratory fitness following aerobic exercise, which points to an important distinction between statistical and clinical significance. Indeed, Hawkins & Wiswell (2003) report that in older adults, VO_{2max} declines 10% per decade. Therefore, our results are clinically significant as they suggest that a relatively short-term intervention can counteract the age-normative decline in cardiorespiratory fitness. Moreover, one reason we may not have observed a statistically significant effect is due to the high baseline cardiorespiratory fitness found in the AE group, which may have limited the possibility for further improvement through training. Based upon the findings from Pothier et al., (2021), which utilized the same population and training design, but had a larger sample size, significant improvements in cardiorespiratory fitness were observed following aerobic exercise training. This therefore points to the potential limitation of our sample which had higher baseline VO_{2peak} values.

Conclusions

The present research elucidates the impact of cognitive or physical training on the separate cognitive and motor components involved in dual tasking and considers how different interventions may work towards improving dual-task behaviour. The results suggest that regardless of training modality (EF, AE, GMA), older adults improved their cognitive performance during dual-task walking, while maintaining their gait speed. This contributes to the growing body of literature which provide evidence for a multiple routes perspective (i.e., Berryman et al., 2014; Desjardins-Crepeau et al., 2016; Fraser et al., 2017; Pothier et al., 2021).

Specifically, this perspective argues that while different forms of cognitive and physical training lead to similar improvements in cognitive or motor performance, they do so through varying mechanisms. For instance, improvements in dual-task performance may have resulted from increasing executive functions following cognitive training, enhancing cardiorespiratory fitness following aerobic exercise, and reducing the metabolic energy demands following gross motor coordination training. Also notable from this research is the cognitive dual-task facilitation that was observed post-training, particularly for older adults with lower baseline cognitive status. This highlights the potential for cognitive enhancement to alter attentional allocation under complex walking conditions in individuals with lower cognitive ability. Our research findings are important given the functional implications of reduced dual-task performance in old age (e.g., increased risk of falls, cognitive impairment). However, due to the limitations of this study, including a small sample size and lack of a control group, future research is needed to substantiate the current study findings, ideally in a larger randomized control trial.

CHAPTER THREE:

Study 2

Frontal Brain Activation During Dual-Task Walking in Middle-Aged and Older Adults Before and After At-Home Computerized Executive-Function Training

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Manuscript prepared to be submitted to Psychology and Aging. Minor changes to formatting and citation style were made to make the manuscript more cohesive with the rest of the dissertation.

Abstract

Background: Cognitive-motor dual-task performance (CMDT: simultaneous completion of a cognitive and motor task) declines with age. A candidate reason for this decline is increased competition for neural capacity that supports both cognitive and motor functioning in old age. Neuroimaging studies during CMDT in both younger and older adults have shown increased prefrontal cortex (PFC) activity from single-task to dual-task, but debate exists over whether this upregulation is accompanied by performance benefits. Additionally, limited research exists on how neural activity during CMDT may differ across middle-aged and older adults or change following cognitive training. As such, this study aimed to explore the relationship between PFC activation and CMDT performance before and after at-home executive function training, across middle-aged and older-adults.

Methods: Sixteen healthy middle-aged (53.94 ± 4.25 years; 8 female**)** and 21 healthy older adults (70.38 ± 2.99 years, 12 female) completed an auditory 2-back task under single-task (standing) and dual-task (treadmill walking) conditions at baseline and following 12 weeks of at-home executive function (EF) training (*n* = 17) or a wait-list control (*n* = 20). Primary outcome measures included cognitive (auditory 2-back reaction time) and gait (stride time variability) performance. Brain activity (oxygenated hemoglobin; HbO, concentration) was measured using functional near-infrared spectroscopy (fNIRS) over the anterolateral, dorsolateral, and ventrolateral PFC.

Results: Linear mixed effect analyses demonstrated improvement following EF training for cognitive dual-task costs (DTCs) (larger magnitude of improvement in participants with higher baseline cognitive functioning) and gait DTCs (greater magnitude of improvement in middle-aged adults with higher cognitive status, and older adults with lower cognitive functioning). We generally found that increased PFC activity from single-task to dual-task predicted lower dual-task costs (suggestive of neural compensation) following EF training, although differential patterns emerged based on age and cognitive status. Individuals who showed a greater magnitude of improvement on the trained tasks tended to show a pattern of neural compensation.

Conclusions: Our results offer novel insights into the potential neural plastic changes underlying improvements in cognition and gait following executive function training, and how this varies according to individual difference factors. Greater cognitive reserve at baseline or increased cognitive resources following executive function training may promote compensatory scaffolding to improve dual-task performance in middle-aged and older adults.

Trial Registration: Identifier: NCT05418998. https://clinicaltrials.gov/ct2/show/NCT05418998

Key words: cognitive training, dual-task, older adults, prefrontal cortex, functional near infrared spectroscopy

Introduction

Maintaining cognitive, physical, and functional capacity is a central concern of healthy aging. Notably, cognition and mobility become increasingly interdependent with age (Demnitz et al., 2016). Evidence for this is largely derived from the cognitive-motor dual-task literature, which demonstrates decrements in gait and cognitive performance when a cognitive load is added to a walking task, with greater performance decrements observed in older adults compared to younger adults (Al-Yaha et al., 2011; Amboni et al., 2013; Smith et al., 2016; Yogev-Seligmann et al., 2008). This has important clinical implications as poor dual-task performance in old age has been associated with an increased risk for falling and cognitive decline, including mild cognitive impairment (MCI) and dementia (Montero-Odasso et al., 2012b; Montero-Odasso et al., 2017; Muir-Hunter & Wittwer, 2016). One potential pathway that has been proposed to underlie the observed dual-task deficits in older adults is competition for shared neural resources and reduced cognitive capacity with age (Li et al., 2018). Specifically, increased cognitive control required to support motor performance in old age may further diminish the already constrained cognitive resources that can be devoted to a secondary cognitive task.

Measurement of brain activity while walking may elucidate the putative neural mechanisms underlying such dual-task deficits to better support this interpretation. Research suggests that dual-task walking results in increased activation in brain regions associated with higher cognitive control, such as the prefrontal cortex (PFC), compared to single-task walking (Hamacher et al., 2015). However, there is inconsistent evidence on whether this upregulation in brain activity is more pronounced in late adulthood (see Kahya et al., 2019, Pelicioni et al., 2019, and Udina et al., 2020 for reviews). Some studies have demonstrated greater PFC activation while dual-task walking in healthy older adults compared to younger adults (Mirelman et al., 2017; Ohsugi et al., 2013), whereas other studies have shown age-invariant levels of brain activity (Fraser et al., 2016; Stuart et al., 2019), or even higher brain activity in younger adults compared to older adults (Beurskens et al., 2014; Holtzer et al., 2011). Theses inconsistencies underscore the importance of investigating the relationship between brain activity and behavioural performance to elucidate whether changes in brain activity with age reflect neural compensation, inefficiency, or dedifferentiation.

According to compensatory theories of cognitive aging (e.g., Scaffolding Theory of Aging and Cognition: STAC; Compensation-Related Utilization of Neural Circuits Hypothesis: CRUNCH), compensation reflects the recruitment of additional neural resources, particularly prefrontal brain regions, in response to age-related structural and functional brain degradation, in order to support cognitive functioning (Cabeza et al., 2018; McDonough et al., 2022; Park & Reuter-Lorenz, 2009; Reuter-Lorenz & Cappel, 2008; Reuter-Lorenz & Park, 2014). In contrast, age-related increases in brain activity may be due to an inefficient neural system, whereby enhanced brain activity does not contribute to or is detrimental to cognitive performance (Zarahn et al., 2007). Finally, alterations in brain activity with age may reflect neural dedifferentiation, such that brain activity becomes less distinctive and selective, which has been associated with poorer cognitive performance (Koen & Rugg, 2019)

There is currently little consensus within the dual-task gait literature regarding the relationship between neuroplastic changes during dual tasking and behavioural performance in older adults (Udina et al., 2020; Kahya et al., 2019; Pelicioni et al., 2019). Indeed, some studies demonstrate a positive association between the change in brain activity from single-task to dual-task and behavioural performance, consistent with a compensatory view. Specifically, increased brain activity has been found to correlate with lower gait speed dual-task costs (DTCs; Maidan et al., 2016), and greater stride length and better cognitive performance during dual-tasking (Holtzer et al., 2015) in healthy older adults, as well as better offline inhibitory control in older adults with MCI (Doi et al., 2013). In contrast, findings from other studies align more with the neural inefficiency perspective, as greater increases in brain activation during dual tasking have been associated with higher gait speed dual-task costs DTCs in individuals with Parkinson's Disease (Maidan et al., 2016), and greater declines in cognitive and gait performance from single- to dual-task in healthy older adults (Stojan et al., 2023). Additionally, Ross et al., (2021) demonstrated that in healthy older adults, reduced cortical thickness in regions implicated in higher order control of gait was associated with increased PFC activity while dual tasking, without associated benefits to behavioural performance, suggestive of neural inefficiency. In examining single-task mobility, Lehmann et al. (2022) also demonstrated that higher prefrontal brain activity was associated with poorer balance performance, suggestive of neural inefficiency. The researchers further demonstrated that age moderated this relationship, such that alterations in brain activity more strongly predicted balance performance in older compared to younger adults (Lehmann et al., 2022). Finally, other research has demonstrated that individual difference factors, such as cognitive capacity, impact brain activity during dual tasking. Specifically, older adults with higher cognitive reserve have been shown to have smaller increases in brain activity from single-task to dual-task, suggestive of increased neural efficiency (Holtzer et al., 2022).

Given such inconsistencies in the literature, further research is needed to elucidate the relationship between dual-task-specific neural activation changes and behavioural performance. Additionally, it remains unclear how this relationship may change as a function of age, with most studies comparing younger adults to older adults, with limited research examining middle-aged adults. Of note, in a study comparing dual-task costs (DTCs) during a walking and memorizing task across younger, middle-aged, and older adults, Lindenberger et al. (2000) found that middle-aged adults had higher cognitive DTCs compared to younger adults, but lower DTCs compared to older adults. In contrast, while middle-aged and older adults demonstrated higher gait DTCs compared to younger adults, there were no significant differences between middle-aged and older adults. These findings suggest a potential trade-off between cognitive and gait domains while dual tasking across the lifespan (e.g., prioritizing gait to the detriment of cognitive performance with age) and raises the question of how neural activity may reflect such postural adaptations.

Given that reduced dual-task performance is a sensitive marker of cognitive and physical decline in older adults, it is imperative to investigate methods to improve dual-task behaviour to maintain functional capacity in late adulthood. Accumulating evidence suggests that in older adults, executive function training can improve dual-task working memory (Downey et al., 2022) and gait performance (Fraser et al., 2017; Smith-Ray et al., 2015; Verghese et al., 2010). It has been suggested that cognitive interventions may enhance compensatory scaffolding in response to age-related declines in cognitive and motor systems by promoting increased cortical activity in regions associated with higher-level cognitive control (Park & Reuter-Lorenz, 2009; Reuter-Lorenz & Park, 2014). However, investigations of the effect of executive function training on brain activity during cognitive-motor dual tasking is limited. To our knowledge, only one study has partially investigated this question using electroencephalography (EEG) during a sensorimotor task (Marusic et al., 2022), with results suggestive of increased neural efficiency following computerized cognitive training (i.e., reduced P2 latency correlated with faster dual-task gait speed). While these results shed light on the potential neural mechanisms underlying training-related improvements in dual-task performance, brain activity was measured during a separate task, rather than during the dual-task, potentially limiting the interpretation of the results.

Research Objectives and Hypotheses

Taken together, there is limited and inconsistent evidence for the potential mechanism(s) underlying cognitive-motor dual-task specific neural activation changes in middle-aged and older adults. Additionally, it remains unclear whether this neural mechanism changes following at-home executive function training, and whether this differs as a function of age. As such, the primary objectives of this study were to 1) examine the association between neural activation changes and behavioural changes from single-task to dual-task at baseline, and explore any age-related differences in this relationship, 2) examine the effect of executive function training versus a wait-list control on cognitive-motor dual-task performance and brain activation across middle-aged and older adults, and 3) investigate the association between changes in dual-task performance and brain activation following executive function training or a wait-list control across middle-aged and older adults. Given findings of neural inefficiency during dual tasking in cognitively unimpaired older adults (e.g., Stojan et al., 2023), it was hypothesized that at baseline, older adults would show a pattern of neural inefficiency (i.e., higher brain activity associated with poorer dual-task performance), whereas middle-aged adults would show less of an association between brain activity and dual-task performance compared to older adults. It was further hypothesized that executive function training would lead to greater improvements in dual-task performance compared to the wait-list control, and that greater improvements would be seen in older adults compared to middle-aged adults. Finally, we predicted a differential pattern of neural plasticity as a function of age following executive function training, such that in older adults, the neural mechanism would change from a pattern of neural inefficiency to neural compensation following training, whereas middle aged adults would show increased neural efficiency (i.e., reduction in brain activity associated with increased dual-task performance).

Methods

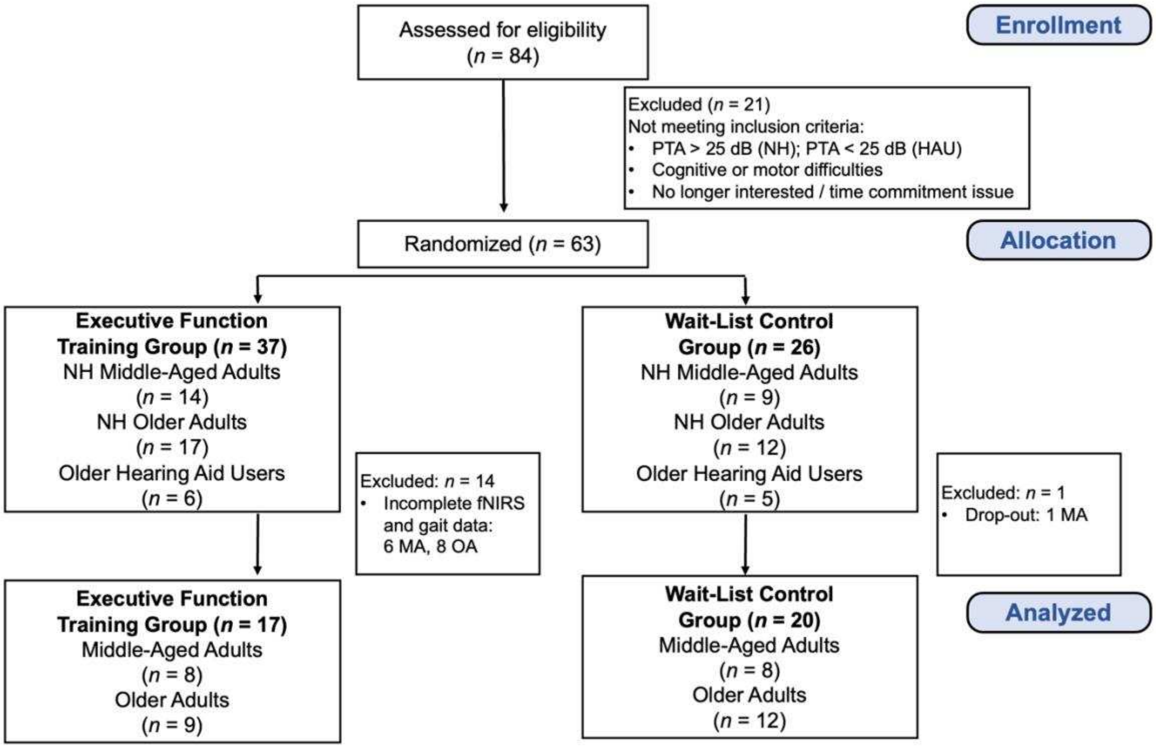
Participants

Participants were included in the study if they were between the ages of 45 and 60 years old (i.e., middle-aged adults) or between the ages of 65 and 80 years old (i.e., older adults), and were fluent English speakers and readers (i.e., monolingual or second language acquired early in life). Participants were screened for cognitive impairment using the Montreal Cognitive Assessment (MoCA; Nasreddine et al., 2005). Participants were included in the study if they scored equal to or above 23/30 on the MoCA and performed within the age-normative range on other neuropsychological tests (see Downey et al., 2022 for further details). Participants were also required to have normal hearing, which was measured using SHOEBOX Audiometry (i.e., pure tone average in the better ear across 500Hz, 1kHz, 2kHz, and 4kHz frequencies below 30 decibels hearing level; World Health Organization, 2021). Participants were included in the study if they had normal or corrected-to-normal vision as measured with the Early Treatment Diabetic Retinopathy Study (ETDRS) chart (Ferris et al., 1982; i.e., required to score 0.08 or below). Participants were excluded from the study if they had a history of a learning disability, attention-deficit hyperactivity disorder, any major psychiatric illnesses (e.g., severe anxiety or depression), any previously diagnosed form of cognitive impairment, or any neurological, cardiovascular, orthopedic, or musculoskeletal conditions that impeded their mobility, concentration, or everyday functioning. Finally, participants who scored below 16/28 on the Mini-BESTest (Franchignoni et al., 2010) were excluded from the study, due to an indication of potential motor difficulties (Yingyongyudha et al., 2016). All participants provided informed consent as approved by Concordia University's Human Research Ethics Committee (Certificate #30,011,799).

In the initial study design, we proposed to investigate the effect of executive function training on cognition and mobility in older adults with either normal hearing or age-related hearing loss who wore hearing aids, as well as normal hearing middle-aged adults (Downey et al., 2023). However, recruitment challenges imposed by the COVID-19 pandemic resulted in a smaller sample size of older hearing aid users ($n = 11$). As such, we opted to only report data from the normal-hearing middle-aged and older adults in the current study to achieve a more balanced design. Based upon initial sample size estimations (see Downey et al., 2023), in order to achieve a power of .95 at an alpha level of .05 for a Time by Training Group interaction effect, we aimed to recruit 20 participants per training group to allow for 10% attrition (i.e., 10 participants in each age group across training groups). A total of 37 participants had complete fNIRS and gait data and were included in the final study analyses: 17 in the Executive Function Training group and 20 in the Wait-List Control group; See Figure 1 for CONSORT flow diagram, and Table 2 for participants characteristics across training groups).

Figure 1

Consort Flow Diagram of Participant Recruitment and Group Allocation



Note. Due to the small and unequal sample size, the older hearing aid users were not included in the current study analyses. Additionally, due to technical issues with registering the start and end of each trial during the dual-task experiment, the gait and fNIRS data were incomplete for 14 participants. The final row depicts the total number of participants included in the study analyses across training groups and age groups.

Measures

Primary outcome measures. The primary outcome measures included tests of single-task and dual-task cognitive and gait performance, as well as oxygenated hemoglobin levels (HbO) during each of these conditions. Participants completed treadmill walking and an auditory working memory task in isolation (i.e., single-task gait: A, single-task cognition: B) or concurrently (i.e., dual-task condition: C). The experiment followed an ABC-CBA design, completed twice, for a total of 12 trials (4 trials per condition).

Cognitive task. An auditory 2-back task (Fraser et al., 2017) was used as the cognitive measure across single- and dual-task conditions. Randomly ordered single digits (1-10, excluding 7) were presented at a rate of one every two seconds, with each trial lasting 30 seconds. Digits were presented through a set of binaural speakers (Logitech Z623 2.1), placed at shoulder level. Participants used two hand-held USB response buttons (Black Box ToolKit hand-held USB response button) to indicate whether the number they heard was the same or different than the number presented *n* steps prior. Response buttons were held in both hands, with each connected to a USB response box with a 2-m cable to allow for natural arm swing while walking. To ensure the stimuli were audible amongst the background noise of the treadmill, participants first completed an auditory 1-back task (i.e., participants indicated whether the number was the same or different than the number presented 1 step previously). The decibel level was continuously reduced until the participant was unable to attain 100 percent accuracy on the 1-back task or indicated that listening became effortful (i.e., if participants endorsed that they needed to strain to understand the digits). The amplitude of the stimuli was then set at this decibel level for the duration of the experiment (i.e., when 100% accuracy was achieved and listening was not effortful). During the 2-back task, participants used the response buttons to indicate if the number was the same or different than the number presented 2 steps previously. During the single-task condition, participants completed the 2-back task while standing, with their feet on the sides of the treadmill (as the treadmill was continuously running to ensure an equal level of background noise across conditions). Accuracy (%) and reaction times (ms) were recorded and averaged across trials in each condition. Additionally, a weighted reaction time measure was calculated for each condition, such that incorrect responses were penalized by being assigned the maximum time duration for each trial (i.e., 2000 ms).

Walking Task. Participants walked on a treadmill at a self-selected speed at a zero percent incline. The speed of the treadmill was gradually increased until the preferred speed was chosen. During single-task conditions, participants walked on the treadmill at their self-selected speed, whereas under dual-task conditions, participants simultaneously completed the 2-back task while walking. To ensure an equal level of background noise across conditions, the treadmill ran at the selected speed for the duration of the experiment. Temporal gait characteristics were measured via two electronic pressure sensors (TeleMyo Direct Transmission System) that were placed under the toe and heel of each shoe sole. A java script was used to identify the mean and standard deviation of stride time (i.e., time elapsed between the first contact of two consecutive footsteps of the same foot).

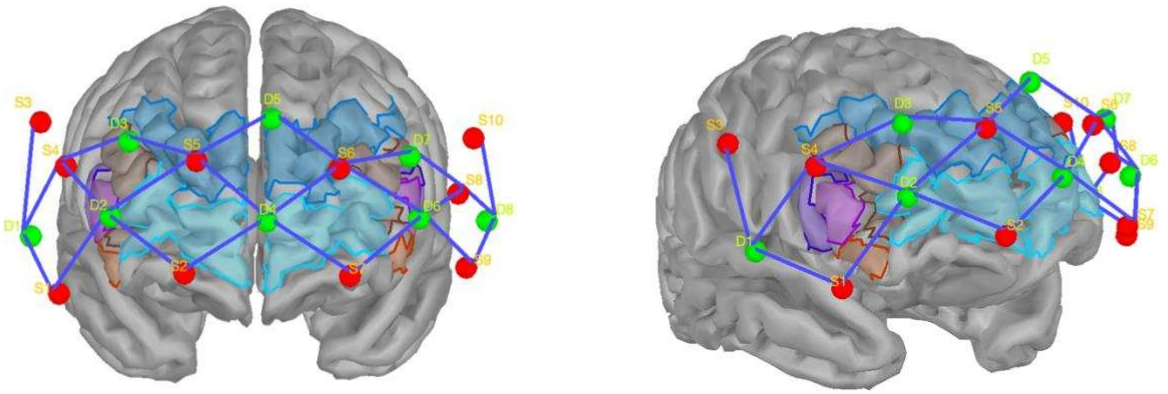
fNIRS Acquisition and Analysis. Frontal brain activation was evaluated under single- and dual-task conditions using functional near infrared spectroscopy (fNIRS; Artinis Brite MKIII, Netherlands). The system contained 10 sources and 8 detectors, spaced 3 cm apart. A standard headcap was used for all participants with the optode placement following a 24-channel frontal template provided by the analysis software OxySoft (Version 3.3.30). The headcap was carefully adjusted to each participant’s head in alignment with the nasion and inion. The positions of the fNIRS optodes were digitized using a neuronavigation system (Brainsight TMS navigation system, Rogue Research Inc., Montreal) and were co-registered based on common landmarks identified on the subject's head and anatomical MRI (nasion, left and right pre-auricular points). The optodes were then projected to the MNI152 template (Fonov et al., 2009; 2011) as a representation of the montage for the group. fNIRS data was recorded continuously at 50 Hz. Changes in oxygenated (HbO) and deoxygenated (HbR) hemoglobin levels were determined using the received optical densities from the 850 and 760 nm wavelengths of near-infrared light, respectively. The overhead lights above the treadmill in the testing room were dimmed to mitigate interference with the optodes. Before starting the experiment, participants were instructed to keep their gaze focused on a fixation cross on the wall facing the treadmill approximately 8 meters away, to avoid sudden head movements, and to avoid speaking during trials or resting periods. A 30-second rest period was also included before each trial (i.e., standing while keeping gaze fixed on the fixation cross). Each rest period served as a baseline comparison for the neural activity in each active trial.

Data pre-processing was conducted using MATLAB (Version R2021b) and the open-source application Brainstorm (Tadel et al., 2011), with the NIRSTORM extension (Delaire et al., 2024). Pre-processing involved 1) visual inspection of motion artifacts in a trial-blind manner, 2) manual segmentation of the three trial types (i.e., single task gait, single-task cognition, dual-task) according to trigger signals, 3) detection and exclusion of bad channels with a coefficient of variation of 10%, 4) application of the modified Beer-Lambert law to convert optical densities to HbO and HbR concentrations and applying a differential pathlength factor correction (Scholkmann, 2013) according to each participants' age, and 5) band pass filtering (0.005Hz-0.1Hz) to eliminate systemic artifacts due to physiological noise (e.g., heartbeat, respiration, slow oscillations from blood pressure fluctuations). All trials were normalized to baseline using a DC offset correction (subtraction of mean over baseline from data to normalize), which was taken during a quiet standing condition spanning -35 to -15 seconds prior to trial onset. HbO and HbR concentrations were then separately averaged across trials per condition. HbO signals, compared to HbR signals, have greater sensitivity to cerebral blood flow and a higher signal-to-noise ratio (Hoshi, 2007; Hoshi et al., 2001; Strangman et al., 2002), leading to better detection of task-evoked changes in brain activity (Plichta et al., 2006; Suzuki et al., 2004), and stronger correlations with fMRI BOLD signals (Cui et al., 2011). As such, this study used HbO concentrations as the primary measure of cortical activation; however, the raw HbR data are available upon request.

After pre-processing, the sensitivity map was used to assign a region of interest (ROI) to each channel. The sensitivity map described the linear relationship between the changes in optical density on the cortex and the changes in optical density at the channel level. Light propagation patterns, or fluences, were computed for each optode for the MNI152 template (Fonov et al., 2009; 2011) using MCXlab, (Fang & Boas, 2009) simulating the propagation of 100 million photons through the head that was segmented into 5 separate tissues (skin, skull, CSF, white- and grey matter) using SPM12. The volumetric fluences were projected on the cortical surface using Voronoi interpolation (Grova et al., 2006). The ROI analysis used the sensitivity map to spatially weight the averages of the measurement channels to test the involvement of a region in group-level analyses. Using the PALS Brodman atlas (Van Essen, 2005), three ROIs were identified across hemispheres: left and right ventrolateral PFC (vlPFC; BA 44, 45, 47), left and right dorsolateral PFC (dlPFC; BA 9, 46), and left and right anterolateral PFC (alPFC: BA 10) (Figures 2 and 3).

Figure 2

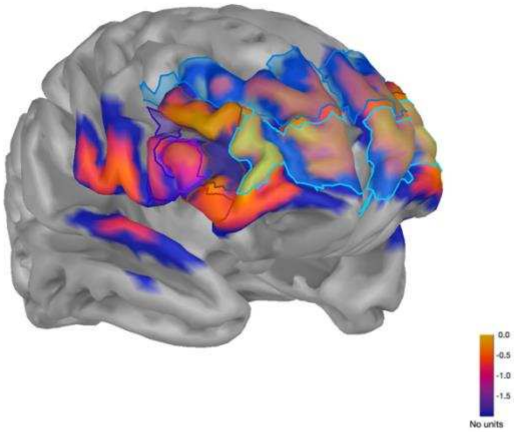
Spatial overlay of the fNIRS channels across the regions of interest



Note. Spatial overlay of the fNIRS sensors (S1-S10; red) and detectors (D1-D8; green) across the three main regions of interest: 1) ventrolateral prefrontal cortex (PFC): BA44 (purple), BA45 (pink), BA47 (orange), 2) dorsolateral PFC: BA9 (dark blue), BA46 (brown), and 3) anterolateral PFC: BA10 (light blue).

Figure 3

Light Sensitivity Map Over the Regions of Interest



Note. Light sensitivity map used to determine which sensor-detector pairs would be included to define our three main regions of interest (vlPFC, dlPFC, alPFC). Yellow is indicative of higher light sensitivity in that region, whereas blue is indicative of lower sensitivity.

Study Design and Procedure

This study was a single-blinded (assessor) randomized controlled trial. Participants were randomly assigned to either the executive function training group or the wait-list control group. Participants in the executive function training group participated in 30-minutes of computerized training aimed at improving divided attention, inhibitory control, and working memory, three times a week for 12 weeks. Participants in the wait-list control group did not complete any form of cognitive training during the 12 weeks and were offered the cognitive training materials at the end of the study. Participants completed a series of cognitive, sensory, and mobility tests across two sessions at baseline and then again following the 12 weeks. Ethical approval was obtained by Concordia University's Human Research Ethics Committee (Certificate #30011799) and the trial was registered with the U.S. National Institutes of Health, Department of Health and Human Services (Identifier: NCT05418998; https://clinicaltrials.gov/ct2/show/NCT05418998). Full details concerning the study procedure are described elsewhere (Downey et al., 2023).

Interventions

Participants randomized to the executive function training group completed an at-home computerized cognitive training program three times a week for a total of 12 weeks (each session lasting 30 minutes). The training protocol involved a custom-written program that has been used in previous research studies assessing cognitive and gait outcomes (e.g., Desjardins-Crepeau et al., 2016; Downey et al., 2022; Fraser et al., 2017; Pothier et al., 2021). Training was comprised of three distinct modules (Stroop, *n*-back, dual-task), which aimed to improve different aspects of executive functioning such as inhibition and task switching, working memory, and divided attention, respectively. Participants completed two of the three modules per session, in alternation across training days. Refer to Downey et al. (2023) for a more detailed description of the training protocol. Program adherence was excellent, with average completion rates of 100% for the dual-task module, 99.7% for the *n*-back module, and 99.2% for the Stroop module. In addition to the training sessions, participants completed an evaluation session prior to starting the first training session and following the last training session, in order to measure near-transfer training effects.

Stroop evaluation task. The stimuli for the Stroop evaluation task consisted of digits (ranging from 1-6) and was comprised of the same four conditions as the training module (i.e., familiarization, reading, inhibition, and switching), in addition to a counting condition. For the familiarization condition, participants were required to press a button/letter key corresponding to the digit presented on the screen. In the reading condition, multiple identical digits were presented in a group, with the identity of the digit being congruent with the quantity of the digits presented (e.g., four copies of the digit "4"), and participants were required to press the button/letter key that corresponded to the digit(s) presented on the screen. In the counting condition, groups of one to six asterisks were presented and the participants were required to report how many asterisks were present. In the inhibition condition, digit(s) were presented on the screen that were incongruent with the quantity of digits presented (e.g., two copies of the digit "5"), and the participants were required to press a button/letter key that corresponded to the quantity of digits presented. In the switching condition, participants were required to alternate between pressing the button/letter key corresponding to the identity of the digit presented on the screen or the quantity of digits, depending on the goal of the trial, as indicated by whether a white frame surrounded the digit(s) or not. Reaction times were computed for each condition, excluding erroneous trials and trials where the reaction time was greater than 4000ms. The primary outcome measure was reaction time for the switching condition, as this most closely reflects our primary behavioural outcome measure (i.e., dual tasking).

N-back evaluation task. The *n*-back evaluation task was comprised of the same three conditions as the training module (i.e., 1-back, 2-back, 3-back), though consisted of digits (ranging from 1-9) instead of letters. An equal proportion of trials was distributed across the three conditions. Reaction times were computed for each condition, excluding erroneous trials and trials where the reaction time was greater than 4000 ms.

Dual-task evaluation task. The dual-task evaluation task was comprised of the same four trial types as the training module (i.e., single-task, dual-task, single-mixed, dual-mixed), though consisted of different stimuli (i.e., fruits and modes of transportation instead of celestial bodies and animals). An equal proportion of trials was distributed across the three conditions. The primary training outcome measure was the dual-task cost score, which was calculated by taking the ratio of the average reaction times (across both hands) for the dual-mixed trials over the single-mixed trials (i.e., dual-mixed trials reaction times – single-mixed reaction times / single-mixed reaction times).

Wait-list control. Participants randomized to the wait-list control group completed both the pre- and post-training assessments but did not partake in any form of cognitive training during the 12-week period. Upon completion of the study, participants in the wait-list control group were offered the materials for the at-home executive function training program, and researchers were available to offer assistance if needed.

Statistical Analyses

All data processing and analyses were completed using Rstudio version 2024.09.1+394 (RStudio Team, 2024). Descriptive statistics were carried out for each variable at each assessment timepoint. Outliers were identified using the boxplot method (i.e., values above the third quartile or below the first quartile range) and corrected using Winsorization (i.e., outliers were replaced with the next most extreme value). Each outcome measure was normally distributed (skew indices ranging from .08 to .49), though were mildly leptokurtic (kurtosis values ranged from 1.82 – 2.41). No transformations were computed to preserve the validity of comparisons across outcome measures and time. Group mean centering of continuous variables was conducted to improve accuracy of slope variance estimates and interpretation of main effects and interactions.

Chi square tests (for categorical variables) and independent sample-tests (for continuous variables) were conducted to determine if there were any differences between age groups and intervention arms at baseline. Separate linear mixed-effect models (LMM) were fitted for each of our outcome measures (i.e., 2-back weighted reaction time, stride time variability, HbO concentrations, and their dual-task costs (i.e., dual-task – single-task) using the *lmer* (Bates et al., 2014) and *lmerTest* packages. The parsimonious model selection procedure (Bates et al., 2015) using a backwards elimination approach was utilized. The initial LMM included fixed effects for Age Group (categorical), Age (continuous), Task or Condition (i.e., single-task, dual-task; single-task walk, single-task cognition, dual-task), Intervention (Executive Function Training, Wait-List Control), Time (pre-, post-training), Region of Interest (alPFC, dlPFC, vlPFC), Hemisphere (left/right), Sex (male/female), Education, PTA, MoCA scores, Mini-BesTest scores, and their interactions. Note that HbO dual-task cost (Δ Activation) was also included as a fixed factor when examining the relationship between behaviour and brain activation (i.e., cognitive dual-task costs and gait dual-task costs were included as the outcome measures). Additional LMMs were conducted using the evaluation training measures from the executive function training group (i.e., Stroop switching reaction times and dual-task DTC change scores from pre- to post-training, wherein lower numbers indicate greater improvement). Random intercepts, including the within-subject differences across cohorts, were included as a nested factor. Models were optimized based on LMM's goodness of fit using the likelihood ratio test. Fixed effects and interactions that did not reliably contribute to model fit were removed, except for confounds (e.g., sex, education) to be consistent with previous literature, as well as instances where the fixed effects or interactions were necessary to evaluate our proposed research question (e.g., four-way interaction between Time, Intervention, Age, and HbO DTCs). See Supplementary Material for detailed model fit estimates.

Results

Initial Data Inspection: Participant Characteristics and Primary Outcome Measures across Age Groups

To address our first research objective (i.e., to evaluate the association between neural activation changes and behavioural changes from single-task to dual-task at baseline, and whether this relationship differs as a function of age), we first inspected the data to determine if there were any significant differences in our participant characteristics and primary outcome measures across age groups. We found significant effects of Age, PTA (older adults had poorer hearing compared to middle-aged adults), and 2-back performance (older adults performed worse than middle-aged adults; Table 1).

Table 1

Descriptive Statistics and Independent Sample T-Tests/Chi Square Tests for Participant Characteristics and Primary Outcome Measures Across Middle-Aged and Older-Adults at Baseline

Variable	Middle-Aged Adults (n = 16)		Older Adults (n = 21)		t or χ^2	p	d
	M	*SD*	*M*	*SD*			
Age (years)	53.94	4.25	70.38	2.99	-13.82	<.001	-4.59
Education (years)	17.94	3.63	17.69	3.46	.21	.834	.07
MoCA (/30)	26.81	1.97	26.43	1.94	.59	.558	.20
Mini-BESTest (/28)	26.00	1.46	25.14	1.59	1.68	.102	.56
PTA (db HL)	11.17	5.15	15.98	6.91	-2.33	.026	-.77
ST RTW (ms)	1129.36	136.46	1239.98	165.53	-2.17	.037	-.72
DT RTW (ms)	1173.23	133.54	1268.89	132.39	-2.17	.037	-.72
ST Stride Time Variability (SD)	.083	.068	.092	.069	-.41	.688	-.14
DT Stride Time Variability (SD)	.071	.047	.087	.070	-.76	.453	-.26
Sex (*n female, %*)	8 (50.00%)		12 (57.14%)		.187	.666	

Note. MoCA = Montreal Cognitive Assessment; BEST = Balance Evaluation Systems Test; PTA = Pure Tone Average; db HL = Decibels hearing level; ST = Single-task; DT = Dual-task; RTW = Weighted reaction time (combination of accuracy and speed performance).

Single- to Dual-Task Changes in Behavioural Performance and the Effect of Age

In further addressing our initial research question, we first wanted to evaluate whether our dual-task manipulation was effective. We found a significant Task effect for cognitive performance, such that reaction times were higher during dual-task compared to single-task, as well as a significant Task effect for stride time variability, such that variability was higher during single-task compared to dual-task (Table 2). We then wanted to evaluate whether behavioural performance differed as a function of age. We found a significant Age Group effect on cognitive performance, such that older adults had significantly higher reaction times compared to middle-aged adults (Table 2). We also found a significant interaction of Age Group, Task, and MoCA for cognitive performance, such that only in middle-aged adults during single-tasking, higher MoCA scores marginally predicted lower reaction times (β = -37.5, *SE* = 20.2, *p* = .08). We further found a significant Age Group effect for stride time variability, such that variability was higher in older adults compared to middle-aged adults (Table 2). Finally, we found a significant Age Group by Task by MoCA interaction for stride time variability, such that only in the middle-aged adults under both single (β =0.015, *SE* = .01, *p* = .01) and dual-task (β =0.016, *SE* = .01, *p* = .01) conditions, higher MoCA scores predicted higher gait variability.

Single- to Dual-Task Changes in Brain Activation and the Effect of Age

In examining baseline corrected regional changes in HbO from single-task to dual-task, we found a significant effect of Condition, with higher HbO levels during dual tasking, compared to both single-task walking and single-task cognition (Table 2). We further found a significant effect of Region, with highest HbO levels within the vlPFC, followed by the alPFC, and then the dlPFC (Table 2). We also found a significant effect of Hemisphere, such that HbO levels were higher in the right hemisphere compared to the left (Table 2). In examining whether brain activation differed as a function of age, we found a significant effect of Age, such that older age predicted an increase in HbO levels (Table 2). Finally, we found a significant Age Group by Condition interaction, such that only during single-task walking, HbO levels were significantly higher in middle-aged adults compared to older adults (Table 2).

Table 2

Linear Mixed Models for Baseline Cognition, Gait, and Neural Activity

Dependent Variable	**Fixed Effect(s)**	***F or t (df)***	***M (SE)***	***p***	η_p^2 ***or*** f^2
2-back RTW (ms)	Task	73.45 (1,400.55)	ST: 1181 (19.5) DT: 1218 (19.5)	<.001	.15
	Age Group	5.90 (1, 25.10)	MA: 1148 (30.9) OA: 1252 (26.8)	.023	.19
	Age Group*Task*MoCA	7.60 (1, 400.77)		.006	.02
Stride time variability (SD)	Task	13.27 (1, 390)	ST: .071 (.006) DT: .067 (.006)	<.001	.03
	Age Group	6.25 (1, 23)	MA: .058 (.011) OA: .079 (.008)	.020	.22
	Age Group*Task*MoCA	27.92 (1, 390)		<.001	.07
HbO levels (µmol/L)	Condition	13.25 (2, 612.63)	ST Cog: 3.65 (.41) ST Walk: 4.94 (.41) DT: 6.07 (.41)	<.001	.04
	Region	39.08 (2, 613.07)	alPFC: 3.71 (.41) dlPFC: 2.77 (.41) vlPFC: 8.17 (.41)	<.001	.11
	Hemisphere	24.08 (1, 612.74)	Left: 4.31 (.40) Right: 5.46 (.40)	<.001	.04
	Age	2.73 (23.18)		.012	.03
	Age Group*Condition	48.76 (2, 611.81)	MA: 6.07(.64) OA: 3.80 (.49)	<.001	.14

Note. Task consisted of two levels: single-task (ST) and dual-task (DT); Condition consisted of three levels: ST cognition, ST walk, DT; Age Group consisted of two levels: older adults (OA) and middle-aged adults (MA); Region consisted of three levels: anterolateral prefrontal cortex (alPFC), dorsolateral prefrontal cortex (dlPFC), and ventrolateral prefrontal cortex (vlPFC); Hemisphere consisted of two levels: left and right; RTW = Weighted reaction time (combination of accuracy and speed performance); HbO = oxygenated hemoglobin; MoCA = Montreal Cognitive Assessment.

Inspection of the Training Data: Participant Characteristics and Primary Outcome Measures Across Intervention Arms

To address our second research objective (i.e., to examine the effect of executive function training versus a wait-list control on cognitive-motor dual-task performance and brain activation across middle-aged and older adults), we first ensured that randomization across intervention arms was effective, finding no significant group differences for any of the participant characteristics or primary outcome measures (Table 3).

Table 3

Descriptive Statistics and Independent Sample T-Tests/Chi Square Tests for Participant Characteristics Across Executive Function Training and Control Groups at Baseline

Variable	Executive Function Training (*n* = 17)		Control (*n* = 20)		*t or* χ^2	*p*	*d*
	M	*SD*	*M*	*SD*			
Age (years)	61.82	9.34	64.50	8.71	.901	.374	.297
Education (years)	17.62	3.36	17.95	3.67	.285	.777	-.553
MoCA (/30)	26.35	1.90	26.80	1.99	.695	.492	-.421
Mini-BESTest (/28)	25.29	1.45	25.70	1.69	.777	.442	.256
PTA (db HL)	13.90	7.43	13.90	5.98	.001	.999	.000
ST RTW (ms)	1201.99	200.24	1183.78	124.35	-.338	.738	-.111
DT RTW (ms)	1230.35	138.16	1225.13	144.27	-.112	.911	-.037
ST Stride Time Variability (SD)	.09	.07	.09	.07	.245	.808	-.576
DT Stride Time Variability (SD)	.09	.08	.08	.05	-.465	.645	-.813
Sex (*n female, %*)	9 (52.94)		11 (55.00)		.016	.900	

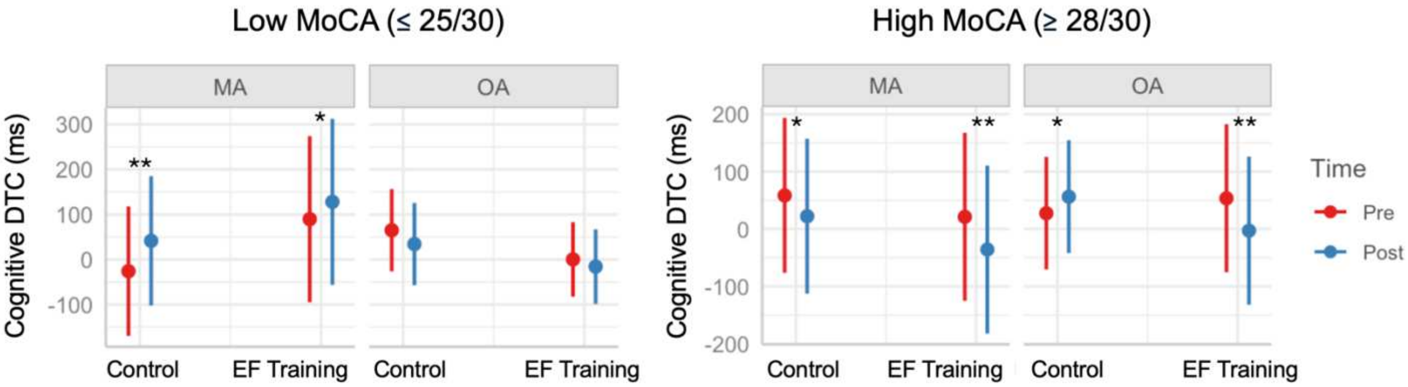
Note. MoCA = Montreal Cognitive Assessment; PTA = Pure Tone Average; db HL = Decibels hearing level; ST = Single-task; DT = Dual-task; RTW = Weighted reaction time (combination of accuracy and speed performance).

Effect of Executive Function Training versus Control on Dual-Task Behavioural Performance Across Age Groups

In examining whether dual-task performance improved following executive function training, and if this differed as a function of age (Research Question 2), we found a significant Time by Intervention interaction effect for cognitive DTCs, $F(1, 394.19) = 5.27, p = .022, \eta_p^2 = .01$, such that DTCs significantly decreased following EF training ($M_{change} = -16.97$ ms, $SE = 5.40, p = .002$, and marginally increased in the Control group ($M_{change} = 9.17$ ms, $SE = 4.68, p = .051$). We further found a significant Time by Intervention by Age Group interaction, $F(1, 394.24) = 10.22, p = .002, \eta_p^2 = .03$, such that cognitive DTCs reduced in older adults following EF training ($M_{change} = -32.81$ ms, $SE = 7.55, p < .001$), whereas DTCs increased in middle-aged adults in the Control group ($M_{change} = 24.45$ ms, $SE = 7.13, p = .001$). Additionally, this three-way interaction was qualified by an interaction with MoCA, $F(1, 394.26) = 10.38, p = .001, \eta_p^2 = .03$, such that in participants with higher baseline MoCA scores (i.e., ≥ 28/30), there was a significant reduction in cognitive DTCs following EF training in older adults and middle-aged adults, a significant, yet lower magnitude of improvement in DTCs following the Control in middle-aged adults, and an increase in DTCs in older adults following the Control. In lower MoCA scorers i.e., ≤ 25/30), DTCs significantly increased following both EF training ($p = .004$) and the Control ($p < .001$) in middle-aged adults (Figure 4).

Figure 4

Linear Mixed Effect Model of Time by Intervention by Age Group by MoCA Interaction Effect on Cognitive Dual-Task Costs

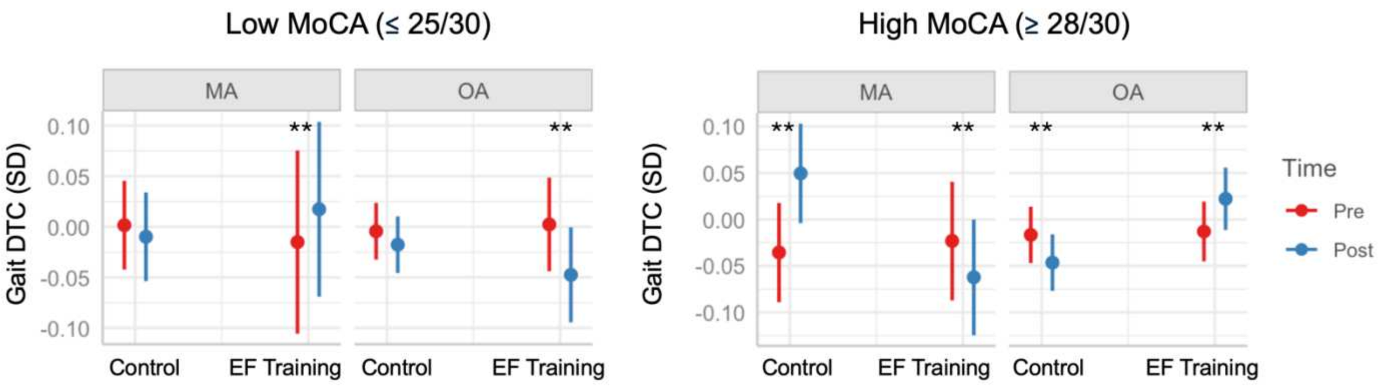


Note. Estimated marginal means of cognitive dual-task costs (i.e., dual-task – single-task for 2-back weighted reaction time scores; higher scores represent increased costs) following Control and Executive Function (EF) Training from pre- (red) to post-training (blue) across participants with lower baseline MoCA performance (left panel) and higher baseline MoCA performance (right panel) in middle-aged (MA) and older adults (OA). The lines represent the error bars which corresponds to the 95% confidence intervals of the estimated marginal means, and the dot represents the mean. MoCA = Montreal Cognitive Assessment; ** = *p* < .001; * = *p* < .05.

Regarding gait DTCs, we found a significant Time by Intervention by Age Group by MoCA interaction, F(1, 384.03) = 74.81, $p < .001$, $\eta_p^2 = .16$, such that in higher MoCA scorers, DTCs significantly decreased in middle-aged adults following EF training and in older adults following the Control, whereas DTCs increased in in middle-aged adults following the Control and in older adults following EF training. In lower MoCA scorers, following EF training, gait DTCs significantly decreased in older adults but increased in middle-aged adults (Figure 5).

Figure 5

Linear Mixed Effect Model of Time by Intervention by Age Group by MoCA Interaction Effect on Gait Dual-Task Costs



Note. Estimated marginal means of gait dual-task costs (DTCs; dual-task – single-task for stride time variability; higher scores represent increased costs) following Control and Executive Function (EF) Training from pre- (red) to post-training (blue) across participants with lower baseline MoCA performance (MoCA ≤ 25/30; left panel) and higher baseline MoCA performance (MoCA ≥ 28/30; right panel) in middle-aged (MA) and older adults (OA). The lines represent the error bars which corresponds to the 95% confidence intervals of the estimated marginal means, and the dot represents the mean. MoCA = Montreal Cognitive Assessment; ** = $p < .001$.

Effect of Executive Function Training versus Control on Dual-Task Neural Activity Across Age Groups

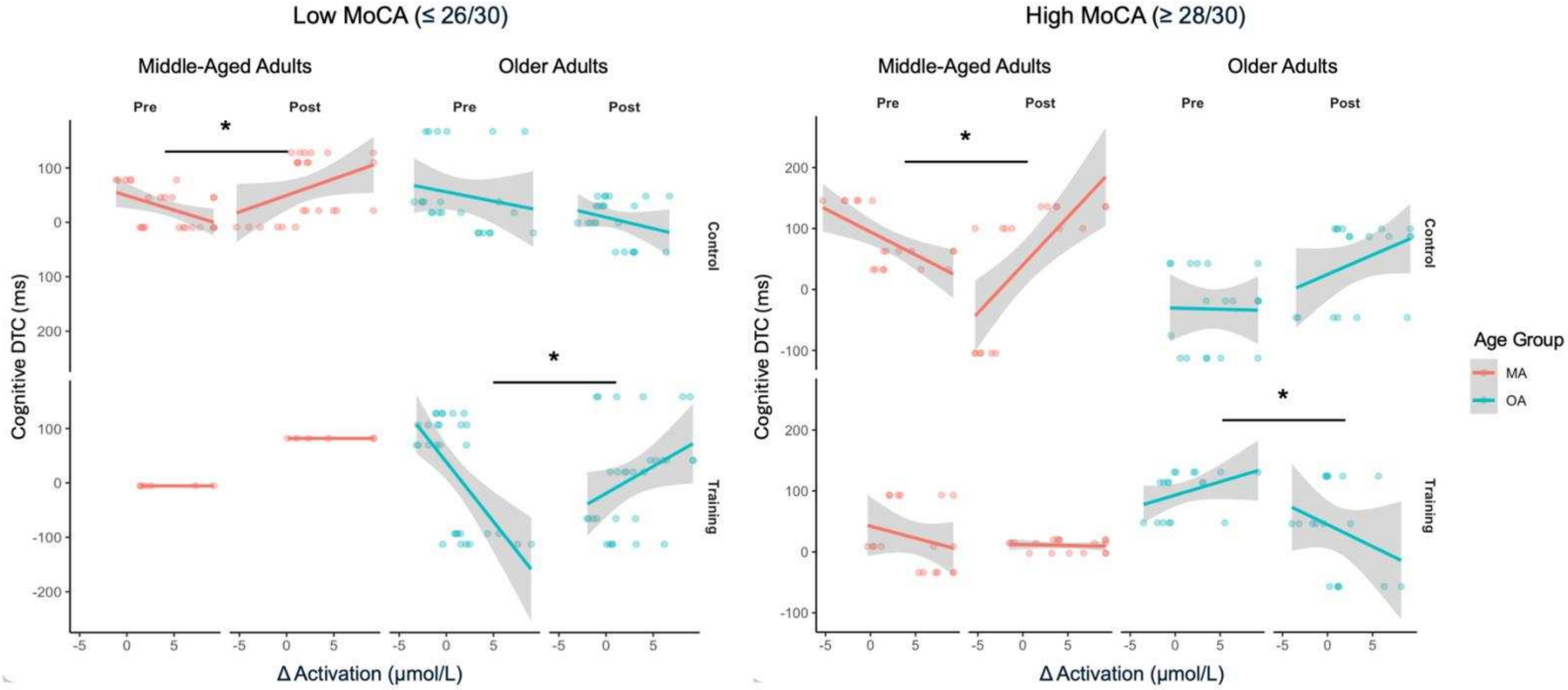
In examining whether the change in neural activation from single-task to dual-task (Δ *Activation*) was altered by executive function training, and whether this differed across age groups, we found a significant Time by Age Group interaction, $F(1, 833.84) = 4.94$, $p = .03$, $\eta_p^2 = .01$. Specifically, Δ *Activation* significantly reduced from pre- to post-training in middle-aged adults only ($M_{change} = -.69$ µmol/L, $SE = .25$, $p = .005$), regardless of the intervention arm.

Effects of Executive Function Training and Age on the Relationship Between Changes in Behavioural Performance and Brain Activation from Single-Task to Dual-Task

In addressing our third research objective (i.e., to investigate the association between changes in dual-task performance and brain activation following executive function training or a wait-list control across middle-aged and older adults), we found a significant five-way interaction between Δ *Activation*, Time, Intervention, Age Group, and MoCA, $F(1, 371.77) = 10.81$, $p = .001$, $\eta_p^2 = .03$ (Figure 6). Specifically, in older adults with higher baseline MoCA scores, the slope between Δ *Activation* and cognitive DTCs significantly decreased following EF training (i.e., at baseline, higher Δ *Activation* predicted higher DTCs, and post-training, higher Δ *Activation* predicted lower DTCs). In contrast, in older adults with lower baseline MoCA scores, the slope between Δ *Activation* and cognitive DTCs significantly increased following EF training (i.e., at baseline, higher Δ *Activation* predicted lower DTCs, and post-training, higher Δ *Activation* predicted higher DTCs). Within the Control group, in middle-aged adults, the slope between Δ *Activation* and cognitive DTCs significantly increased over time (i.e., at baseline, higher Δ *Activation* predicted lower DTCs, and following 12 weeks, lower Δ *Activation* predicted lower DTCs), with the magnitude of change being greater in the middle-aged adults with higher baseline MoCA performance.

Figure 6

Linear Mixed Effect Model of Δ Activation by Time by Intervention by Age Group by MoCA Interaction Effect on Cognitive Dual-Task Costs



Note. Regression slopes between *Δ Activation* (i.e., dual-task – single-task for HbO concentrations) and Cognitive DTCs (i.e., dual-task – single-task for 2-back weighted reaction time scores) pre- and post-training across Control (top panel) and Executive Function Training (bottom panel) groups, middle-aged (MA; orange) and older (OA; blue) adults, and participants with lower baseline MoCA performance (MoCA ≤ 26/30; left panel) and higher baseline MoCA performance (MoCA ≥ 28/30; right panel). Each dot represents an individual data point, and the shadows represent the 95% confidence intervals of each regression line. Scores above zero represent increased reaction time scores or increased brain activity, during dual tasking relative to single tasking.

Regarding the relationship between gait DTCs and brain activity following training across age groups, we found a significant four-way interaction between Δ *Activation*, Time, Intervention, and Age Group, $F(1, 324.2) = 5.48$, $p = .02$, $\eta_p^2 = .02$. Specifically, in the Control group, the regression slope between Δ *Activation* and gait DTCs significantly increased in both older adults ($M_{change} = .006$, $SE = .001$, $p < .001$) and middle-aged adults, though the magnitude of change was smaller in the middle-aged adults ($M_{change} = .002$, $SE = .001$, $p < .001$). Specifically, in both middle-aged and older adults, at baseline, higher Δ *Activation* predicted lower gait DTCs, whereas post-training, higher Δ *Activation* predicted greater DTCs.

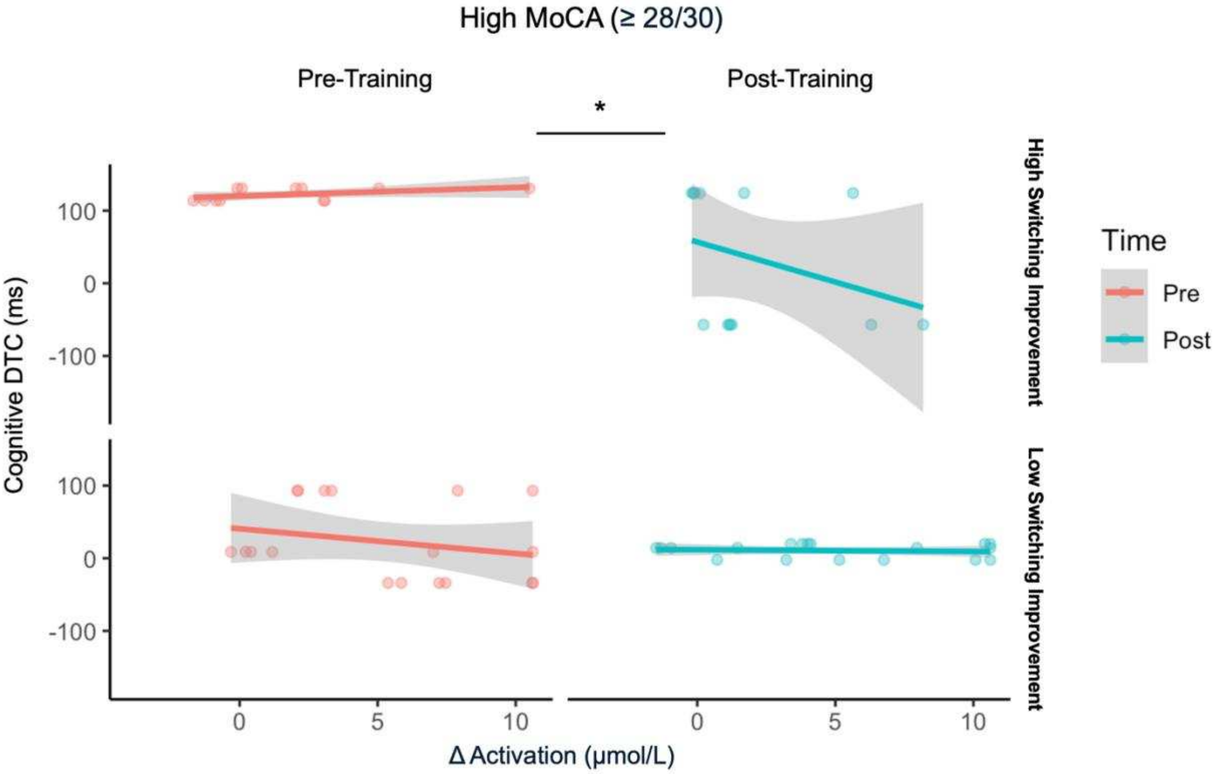
Effect of Training Response on the Relationship Between Changes in Behavioural Performance and Brain Activation from Single-Task to Dual-Task

To better understand the association between Δ *Activation* and behavioural performance from single-task to dual-task following executive function training, we conducted *post hoc* analyses examining whether the magnitude of improvement on the computerized executive function near-transfer tasks (i.e., dual-task DTC scores [Divided Attention] and Stroop switching reaction time scores [Switching] from the evaluation sessions) influenced the relationship between neural activity and behavioural performance. For the cognitive DTCs, we found a significant Δ *Activation* by Divided Attention by Time interaction, $F(1, 162.11) = 6.99$, $p = .009$, $\eta_p^2 = .04$, such that in participants who showed a greater degree of improvement in divided attention from pre- to post-training, the regression slope between Δ *Activation* and cognitive DTCs significantly increased, though remained negative following Executive Function training (i.e., higher Δ *Activation* predicted lower DTCs; $M_{change} = 6.49$, $SE = 3.03$, $p = .034$). In participants who had a lower degree of improvement on the divided attention near-transfer task, the regression slope marginally decreased, though remained positive following training (i.e., higher Δ *Activation* predicted higher DTCs; M_{change} = - 5.10, *SE* = 3.08, *p* = .09).

We further found a significant Δ *Activation* by Switching by Time interaction, *F*(1, 136.16) = 4.01, *p* = .047, η_p^2 = .03, such that in participants who showed a greater magnitude of improvement on the task-switching near-transfer task, the regression slope between Δ *Activation* and cognitive DTCs marginally decreased following training (i.e., higher brain activity predicted lower DTCs; M_{change} = -9.34, *SE* = 5.89, *p* = .11). In contrast, in participants who had a lower degree of task-switching improvement, the slope between Δ *Activation* and cognitive DTCs marginally increased following training, such that higher neural activity from single-task to dual-task predicted higher DTCs (M_{change} = 8.14, *SE* = 4.66, *p* = .08). Finally, we found a significant 4-way interaction between Δ *Activation*, Time, Switching, and MoCA, *F*(1, 136.34) = 6.23, *p* = .014, η_p^2 = .04, such that the slope between Δ *Activation* and cognitive DTCs only significantly decreased following training in participants who had both high baseline MoCA performance, and who showed a high magnitude of improvement on the task-switching near-transfer task (i.e., higher Δ *Activation* predicted lower DTCs; M_{change} = -26.53, *SE* = 9.82, *p* = .008; Figure 7).

Figure 7

Linear Mixed Effect Model of Δ Activation by Stroop Switching by Time by MoCA Interaction Effect on Cognitive Dual-Task Costs Following Executive Function Training

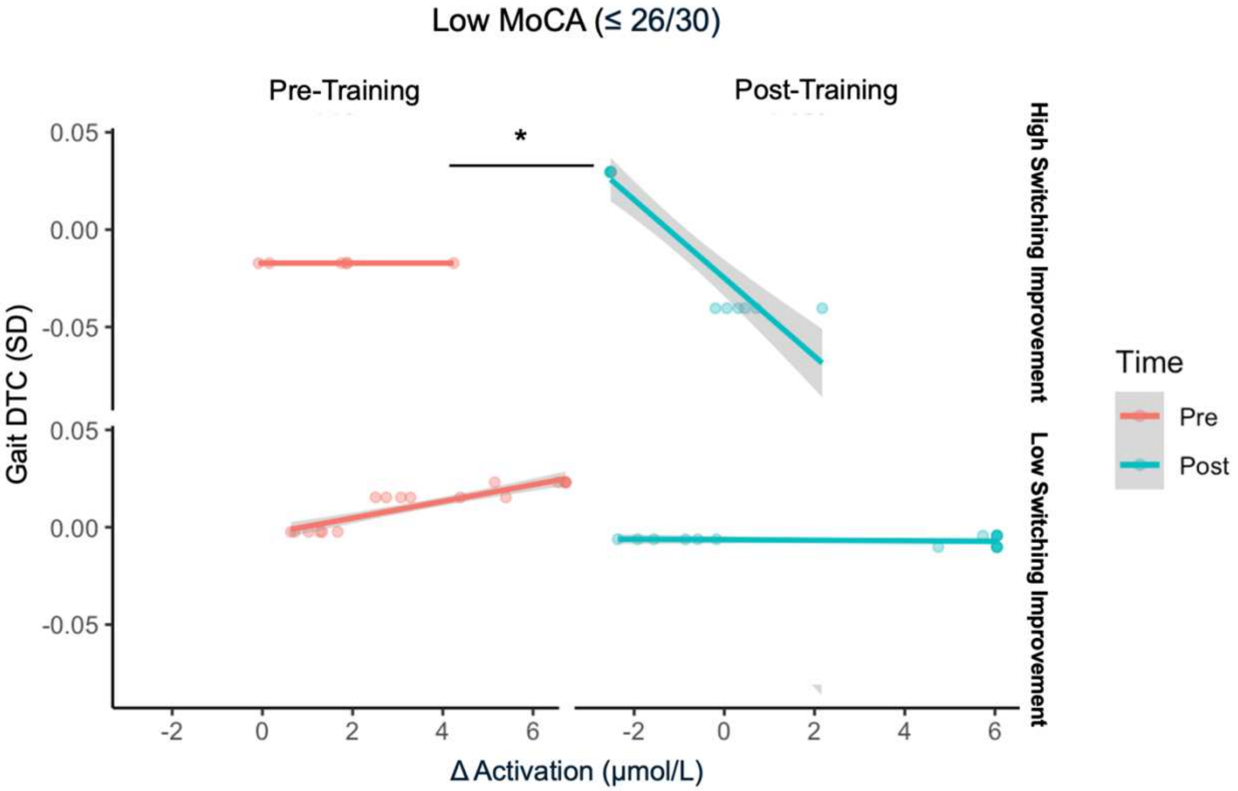


Note. Regression slopes between *Δ Activation* (i.e., dual-task – single-task for HbO concentrations) and Cognitive DTCs (i.e., dual-task – single-task for 2-back weighted reaction time scores) pre- (orange) and post- (blue) Executive Function Training in participants with high baseline MoCA performance (MoCA ≥ 28/30), and across participants who showed a high magnitude of improvement in the task-switching near-transfer task (i.e., reaction times improved by 433 ms - one standard deviation below the mean; top panel) and a low magnitude of improvement (i.e., reaction times improved by 133 ms – one standard deviation above the mean; bottom panel). Each line represents the regression slope, and the shadows represent the 95% confidence intervals of each regression line. Scores above zero represent increased reaction time scores or increased brain activity, during dual-tasking relative to single-tasking.

With regards to the Gait DTCs, we found a significant Δ *Activation* by Divided Attention by Time by Age interaction, $F(1, 145) = 4.80$, $p = .03$, $\eta_p^2 = .03$, such that the slope between Δ *Activation* and Gait DTCs following training significantly decreased in younger participants (< 55 years old) who showed the greatest degree of improvement in divided attention (i.e., higher Δ *Activation* predicted lower gait DTCs; $M_{change} = .006$, $SE = .003$, $p = .018$). In contrast, the slope between Δ *Activation* and Gait DTCs following training significantly increased in older participants (> 70 years old) who showed the greatest degree of improvement in divided attention (i.e., lower Δ *Activation* predicted lower gait DTCs and higher Δ *Activation* predicted higher gait DTCs; $M_{change} = .003$, $SE = .001$, $p = .02$). We further found a significant Δ *Activation* by Stroop by Time by MoCA interaction, $F(1, 134) = 5.66$, $p = .018$, $\eta_p^2 = .04$, such that the slope between Δ *Activation* and Gait DTCs only significantly decreased following Executive Function training in participants who had low baseline MoCA performance and who showed the greatest magnitude of improvement in the Stroop Switching task (i.e., higher Δ *Activation* predicted lower gait DTCs; Figure 8). Finally, we found a significant Δ *Activation* by Stroop by Time by Age interaction, $F(1, 134) = 4.01$, $p = .047$, $\eta_p^2 = .03$, such that there was only a significant decrease in the slope between Δ *Activation* and Gait DTCs following training in younger participants ($M_{age} < 55$) who showed a greater magnitude of improvement on the Stroop Switching task (i.e., higher Δ *Activation* predicted lower gait DTCs; $M_{change} = .003$, $SE = .001$, $p = .034$).

Figure 8

Linear Mixed Effect Model of Δ Activation by Stroop Switching by Time by MoCA Interaction Effect on Gait Dual-Task Costs Following Executive Function Training



Note. Regression slopes between *Δ Activation* (i.e., dual-task – single-task for HbO concentrations) and Gait dual-task costs (i.e., DTCs = dual-task – single-task for stride time variability) pre- (orange) and post- (blue) Executive Function Training in participants with low baseline MoCA performance (MoCA ≤ 26/30), and across participants who showed a high magnitude of improvement in the task-switching near-transfer task (i.e., reaction times improved by 433 ms - one standard deviation below the mean; top panel) and a low magnitude of improvement (i.e., reaction times improved by 133 ms – one standard deviation above the mean; bottom panel). Each line represents the regression slope, and the shadows represent the 95% confidence intervals of each regression line. Scores above zero represent increased stride time variability or increased brain activity, during dual-tasking relative to single-tasking.

Discussion

In the current study, we investigated the relationship between cognitive-motor dual-task performance and frontal brain activation at baseline and following twelve weeks of at-home computerized executive function training and explored the differences in this relationship across middle-aged and older adults. At baseline, we found that increased brain activation from single-task to dual-task predicted better behavioural performance from single-task to dual-task (i.e., faster 2-back reaction time scores, reduced stride time variability), particularly in older adults. Next, we found that executive function training improved cognitive dual-task performance, particularly in middle-aged and older adults with higher baseline cognitive functioning (i.e., MoCA scores). Additionally, dual-task gait performance improved following executive function training in middle-aged adults with higher cognitive functioning and, in contrast, in older adults with lower cognitive functioning. With regards to the effect of training on the brain-behaviour relationship, we found that in older adults with higher baseline cognitive functioning, neural upregulation predicted lower cognitive DTCs following executive function training (possibly suggestive of neural compensation), whereas in older adults with lower baseline cognitive functioning, neural upregulation predicted higher cognitive DTCs, whereas reduced brain activity predicted lower DTCs. For middle-aged adults in the wait-list control group, neural upregulation predicted greater DTCs, which may reflect a pattern of neural inefficiency. We further found that in participants who showed a greater magnitude of improvement on the near-transfer tasks, neural upregulation predicted lower cognitive DTCs, particularly in individuals with higher baseline cognitive functioning, and predicted lower gait DTCs, particularly in younger participants or those with lower baseline cognitive functioning.

Relationship Between Brain Activity and Dual-Task Performance Across Middle-Aged and Older Adults

In contrast to our hypotheses that predicted a pattern of neural inefficiency in older adults at baseline (i.e., higher brain activation from single-task to dual-task associated with higher cognitive and gait DTCs), we found that neural upregulation predicted better cognitive and gait dual-task performance. This relationship was only found in older adults and not in middle-aged adults, suggesting that the observed neural upregulation may reflect a compensatory mechanism that develops with increasing age. This finding is consistent with compensatory theories of cognitive aging (e.g., STAC, CRUNCH), which suggest that with age, additional neural resources are recruited to compensate for age-related structural brain degradation and to support cognitive functioning (Cabeza et al., 2018; McDonough et al., 2022; Park & Reuter-Lorenz, 2009; Reuter-Lorenz & Cappel, 2008; Reuter-Lorenz & Park, 2014).

Our findings join a small literature that links upregulation of prefrontal brain regions to behavioural improvements in cognitive-motor dual-task performance; however, other evidence supports the neural inefficiency perspective. For example, in a study by Maidan et al. (2016), cognition (i.e., serial 3 subtractions), gait (i.e., velocity, stride length), and neural activation (HbO concentrations in PFC) were examined under single-task, dual-task, and obstacle negotiation conditions in individuals with Parkinson’s Disease (PD) and healthy older adults. The authors found that in the healthy older adults, a large increase in brain activity from single-task to dual-task coincided with lower gait speed DTCs, whereas in the PD individuals, a small increase in brain activity from single-task to dual-task coincided with higher gait speed DTCs. These findings suggest a differential brain-behaviour relationship while dual tasking according to clinical status and level of cognitive and physical resources available (i.e., a pattern of neural compensation in healthy older adults, and neural inefficiency in PD individuals). In contrast, in a study by Stojan et al. (2023), neural activation (i.e., HbO concentrations in the PFC and parietal lobe), gait (i.e., step time variability) and cognition (i.e., serial 3 subtractions, Stoop inhibition) were measured under single- and dual-task conditions in healthy older adults in a virtual walking environment. The authors found that increased brain activation (particularly in the PFC) correlated with reduced gait and cognitive performance from single-task to dual-task, which was interpreted as a pattern of neural inefficiency. While the participants included in the study by Stojan et al. (2023) appeared similar to those included in the current study (i.e., similar older adult age range, cognitive ability, etc.), our dual-task experiments slightly differed, which may account for some of the differences observed in the brain-behaviour relationship. Specifically, while both of our experiments were conducted using treadmills, Stojan et al. (2023) implemented a virtual reality environment, which could have increased task complexity, leading to a pattern of neural inefficiency. Given such inconsistencies, future work might consider individual differences in brain structure as another potential moderator of functional brain-behaviour relationships.

Taken together, whether neural inefficiency or compensation is evidenced during dual tasking may differ according to the level of task complexity, level of cognitive or physical resources available to the individual, and/or level of structural brain integrity, which may be altered as a function of age. For example, when task demands surpass the level of cognitive or neural resources available to the individual, this may result in a pattern of neural inefficiency. In contrast, when sufficient cognitive resources are available to meet the associated task demands, we may see a pattern of neural compensation (e.g., in older adults with reduced structural brain integrity), or no relationship (e.g., in middle aged adults with more preserved brain integrity).

This is consistent with behavioural findings in the cognitive-motor dual-task literature, such that with increasing cognitive task complexity, there is a greater reduction in dual-task performance, particularly in healthy older adults compared to younger adults (e.g., Decker et al., 2016; Lövdén et al., 2008; Srygley et al., 2009), and in cognitively impaired older adults (e.g., Hunter et al., 2018). These findings may suggest that with increasing cognitive-motor dual-task demands, there is greater competition for attentional resources, which may lead to increased brain activity to support dual-task performance when there are sufficient resources available (i.e., neural compensation) or increased brain activity that occurs at the detriment to dual-task performance when adequate resources are not available (i.e., neural inefficiency).

Effect of Executive Function Training on Dual-Task Performance Across Middle-Aged and Older Adults

Partially in line with our hypotheses, cognitive-motor dual-task performance generally improved following executive function training, though the magnitude and direction of change varied according to age, level of cognitive status, and task domain. Specifically, following executive function training, cognitive DTCs improved in middle-aged and older adults with higher baseline cognitive status, whereas dual-task cognitive performance worsened in middle-aged adults with lower cognitive functioning. Furthermore, gait DTCs improved following training in older adults with lower cognitive functioning and in middle-aged adults with higher cognitive status, while dual-task gait performance worsened in older adults with higher cognitive functioning and in middle-aged adults with lower baseline cognitive status. Regarding the results following the control, we found that cognitive DTCs mildly improved in middle-aged adults with higher baseline cognitive status (though to a lesser magnitude compared to the executive function training), which may represent practice effects. In contrast, both cognitive and gait dual-task performance declined in middle-aged adults with lower cognitive functioning. In older adults with higher cognitive functioning, cognitive DTCs worsened, whereas gait DTCs improved following the control.

Our findings are partially consistent with previous research demonstrating the beneficial effect of computerized executive function training on dual-task gait and cognitive performance in healthy older adults (e.g., Downey et al., 2022, Fraser et al., 2017; Smith-Ray et al., 2015; Verghese et al., 2010). Our study extends these findings by providing evidence of the potential efficacy of at-home cognitive training, reducing some of the potential confounding factors such as social interactions and physical activity required to commute to in-person training sessions. We further extend these findings by considering how individual differences, such as age and baseline cognitive status, influence training efficacy. We have previously shown that in older adults, lower baseline MoCA performance predicts a greater magnitude of improvement in cognitive DTCs following executive function training, aerobic exercise, and gross motor coordination training (Downey et al., 2022). Interestingly, in the current study, we found somewhat conflicting results (i.e., higher baseline cognitive functioning predicted improvement in cognitive DTCs, while lower cognitive functioning predicted a greater magnitude of improvement in gait DTCs). By considering middle-aged adults, we further demonstrated that higher baseline cognitive functioning conferred greater benefit for both cognitive and gait DTCs following executive function training, whereas lower baseline cognitive status led to poorer dual-task performance following training.

Our results appear consistent with a magnification account of training (e.g., Kliegel et al., 1990; Lövden et al., 2012; Verhaeghen et al., 1996), which was initially proposed to better understand mnemonic training gains, and which purports that cognitive abilities are positively correlated with the magnitude of training improvements. Specifically, it is suggested that individuals with greater cognitive resources have a higher capacity to acquire, implement, and strengthen effortful cognitive strategies, leading to improved cognitive performance following training. Given that in the current study, the executive function training was completed at home with less assistance from researchers, our results suggest that higher cognitive functioning may be required to understand and implement the strategies optimally. In contrast, lower baseline cognitive status appears detrimental for both cognitive and gait dual-task performance in middle-aged adults following training, possibly due to limited uptake and implementation of executive function strategies while dual tasking.

Higher baseline cognitive functioning may also be detrimental to the prioritization of tasks in older adults, as those with higher cognitive functioning demonstrated a reduction in dual-task gait performance following executive function training. This finding is somewhat inconsistent with the well-established "posture-first" strategy (Li et al., 2001; Shumway-Cook et al., 1997), which suggests that older adults tend to prioritize walking performance to the detriment of the secondary cognitive task performance, possibly to increase safety and reduce the risk of falls. However, it is possible that the older adults with higher cognitive functioning implemented a posture-first strategy at baseline, though inherently prioritized cognitive performance following training due to increased self-efficacy in both their cognitive and physical abilities, having less of a concern for falling. In contrast, older adults with lower baseline cognitive status demonstrated an improvement in gait DTCs following training (with relatively little change in cognitive DTCs), potentially due to increased cognitive resources being allocated to the walking task. We did not find this trade-off between task domains in middle-aged adults (i.e., those with higher cognitive functioning improved both cognitive and gait DTCs following training), suggesting that postural prioritization may only develop after a certain age, or once cognitive and physical resources diminish to a level that would pose a risk of falling.

Effect of Executive Function Training and Age on the Relationship Between Brain Activity and Dual-Task Performance

With regards to the effect of training on the relationship between brain activity and dual-task performance, we found a differential pattern of neural plasticity depending on age and baseline cognitive status. Specifically, in older adults with higher baseline cognitive status, an increase in brain activity from single-task to dual-task predicted lower cognitive DTCs following executive function training. This result appears to be in line with both a compensatory neural mechanism and a magnification account of training, such that higher cognitive capacity at baseline may have allowed for increased neural resources to be recruited following training to support dual-task performance. In contrast, in older adults with lower baseline cognitive status, neural upregulation predicted higher cognitive DTCs. This finding appears to be more in line with a pattern of neural inefficiency, such that participants with poorer cognitive functioning may have had a lower capacity to acquire and implement the executive function strategies leading to an inefficient utilization of neural resources while dual tasking. Additionally, in both middle-aged and older adults (regardless of baseline cognitive status), neural upregulation predicted poorer dual-task gait performance following the wait-list control, which may be interpreted as a pattern of neural inefficiency.

To our knowledge, no previous research has directly examined the effect of executive function training on the relationship between neural activity and behavioural performance during cognitive-motor dual tasking. While a few studies have examined the relationship between brain activity during offline cognitive tasks with dual-task performance following other forms of cognitive training (e.g., Marusic et al., 2022; Pellegrini-Laplagne et al., 2023), our results appear generally inconsistent with what has been reported in these studies. Specifically, Pellegrini-Laplagne et al. (2023) measured HbO concentrations over the prefrontal cortex and cognitive performance (i.e., working memory, mental flexibility) before and after computerized cognitive training, aerobic exercise, and simultaneously combined cognitive and exercise training in healthy older adults. The authors reported improvements in mental flexibility, regardless of the training arm, and a reduction in HbO levels during the mental flexibility tasks following the cognitive training only. The authors interpreted this finding to reflect a decreased level of neural activation required to complete the tasks following training (i.e., a pattern of increased neural efficiency). Furthermore, Marusic et al. (2022) found evidence of neural efficiency in healthy older adults following cognitive training using EEG. Specifically, the authors reported shorter foot reaction time responses (during a simple visual reaction time test) with enhanced neural activation over sensorimotor areas (i.e., reduced visual-evoked potential latencies; reduced peak amplitude of motor responses), as well as a negative correlation between the visual-evoked potential latency and dual-task gait speed (i.e., lower latency associated with faster gait speed; Marusic et al., 2022). Finally, in a study using fMRI to investigate the relationship between brain activity and cognitive dual-task processing (without a motor demand) following divided attention training, Erickson et al. (2007) found evidence of both neural compensation and neural efficiency, depending on the brain region being investigated. Specifically, following training, increased dual-task processing was associated with decreased activity in the anterior cingulate, right ventral inferior frontal gyrus, right superior parietal lobule, left superior parietal lobule, and right dorsal inferior frontal gyrus. In contrast, increased executive control was associated with increased activity in the left and right dlPFC following training (Erickson et al., 2007).

Taken together, the finding of increased neural efficiency or compensation following cognitive training appears mixed in the literature. Of note, none of the aforementioned studies directly examined the brain-behaviour relationship during cognitive-motor dual-tasking, which may suggest a differential pattern of neural adaptation following cognitive training, depending on the nature of the task and associated task demands. Interestingly, in a study examining the effect of cognitive training, alone or in combination with exercise on gait speed and structural brain changes in older adults, it was found that following combined training, brain volume and thickness increased, which correlated with increased gait speed (Stein et al., 2024). As changes in brain structure were not examined in the current study, the findings from Stein et al. (2024) highlight the potential role that brain structure may play when interpreting changes in brain activity following training. Indeed, according to compensatory theories of cognitive aging, it is proposed that cognitive interventions may enhance neural scaffolding to counteract age-related structural brain decline, by enhancing cortical activity in regions associated with higher-level cognitive control (Reuter-Lorenz & Park, 2014). In effect, structural brain degradation may stimulate compensatory scaffolding to enhance cognitive performance. However, it remains unclear whether neural upregulation would remain following training where structural brain plasticity is also induced (e.g., increased brain volume, thickness). Future research examining both structural and functional brain changes during dual tasking following cognitive training may therefore be warranted.

Effect of Responsivity to Training on the Relationship Between Brain Activity and Dual-Task Performance

We further conducted *post hoc* analyses to examine whether the magnitude of improvement on near-transfer tasks influenced the relationship between neural activity and dual-task performance following training. We found that in participants who demonstrated a larger magnitude of improvement on the near-transfer executive function tasks (e.g., Stroop switching divided attention), higher PFC activity predicted lower cognitive DTCs following training (i.e., neural compensation). In contrast, in participants who demonstrated a lower magnitude of improvement on the tasks, higher brain activity predicted poorer cognitive dual-task performance (i.e., neural inefficiency). Our results were further influenced by individual difference variables, such as age and baseline cognitive status. Specifically, higher brain activity predicted lower cognitive DTCs only in participants with higher baseline cognitive functioning and a high degree of improvement on the near-transfer tasks. However, higher brain activity predicted lower gait DTCs, only in participants with lower baseline cognitive status and a larger magnitude of improvement on the near-transfer tasks. Finally, neural compensation following training (i.e., higher brain activity predicted lower gait DTCs) was found in younger participants (i.e., < 55 years old) who showed a greater degree of improvement on the near-transfer tasks.

These results highlight how increased training responsivity, as demonstrated by improvements on near-transfer executive function tasks, may have enhanced opportunity for neural upregulation/scaffolding to improve dual-task performance following training. While the relationship between neural activity and dual-task performance following executive function training appeared to follow a pattern of neural compensation, depending on the domain being measured (i.e., cognitive vs. motor) and individual difference variables, the effect of training appeared to follow either a magnification or compensation process (Lövden et al., 2012). Specifically, the increase in brain activity and associated improvement in cognitive DTCs in participants with higher baseline MoCA scores who showed a high degree of improvement on the near-transfer tasks appears to follow a magnification process. As previously described, magnification may occur in individuals with higher cognitive capacity, allowing for more efficient acquisition, implementation, and strengthening of the trained tasks. Increased PFC activity may therefore reflect neural plasticity in response to acquiring and implementing new skills (i.e., divided attention, working memory, updating), particularly in individuals with higher cognitive capacity and who responded well to the executive function training.

In contrast, regarding gait DTCs, the training effects appeared to follow either a compensation or magnification account of training, depending on how the level of cognitive resources were characterized. Specifically, when using age as a marker of cognitive resources, we found that in younger participants who showed a higher degree of improvement on the near-transfer tasks, neural upregulation predicted a greater improvement in gait DTCs. This appears consistent with a magnification process, as cognitive resources tend to be more preserved in middle-aged adults compared to older adults. In contrast, when using baseline MoCA performance as a proxy for cognitive resources, our results appear more consistent with a compensation account of training, given that in participants with lower cognitive functioning, neural upregulation predicted reduced gait DTCs. This theory posits that when intervention task demands exceed available resources, repeated training induces neural plasticity and promotes a higher level of change in performance following training (Lövden et al., 2012). This was evident in our training results, which demonstrated that in older adults with lower baseline cognitive performance, gait DTCs significantly improved following executive function training. Our findings are also partially consistent with other studies which have demonstrated that following a lifestyle intervention (i.e., exercise, cognitive training, dietary advice, vascular risk management), participants with greater subjective memory complaints showed a higher magnitude of improvement in memory performance (Vaskivuo et al., 2025). Taken together, our findings suggest the possibility of differential training processes (i.e., magnification vs. compensation) on the neural compensation observed in individuals who responded well to the executive function training, depending on individual differences factors (i.e., age, baseline cognitive performance), and the domain being measured (i.e., cognitive vs. gait).

Limitations

While the current study provides valuable insights into the relationship between brain activity and dual-task performance before and after executive function training, there are certain limitations that may impact the interpretation of the results. Firstly, due to technical issues that affected the collection of fNIRS and gait data, our sample size was relatively small, with a smaller representation of middle-aged adults compared to older adults. Small sample sizes may affect results from linear mixed effect models in several ways, including the possibility of overfitting a model (i.e., small sample size relative to number of predictors may capture noise rather than an underlying pattern) and convergence issues (i.e., the algorithm might not reach an optimal solution, leading to errors in the results). When selecting our models, we prioritized model simplicity to avoid overfitting (i.e., only including predictors that were theory-driven, relevant to our hypotheses, and significantly contribute to model fit), and we included random intercepts for participants to help account for individual variability. However, some of our results demonstrating complex interaction effects (e.g., 5-way interactions) should be interpreted with caution as our small sample size may have reduced reliability of the parameter estimates.

Another possible limitation of the current study is that we did not include an active control group, but rather a wait-list control. While an active control group may have helped isolate specific effects of the training program by ruling out potential improvements due to unrelated factors such as novelty or increased engagement, previous research using the same executive function training protocol as the current study, which also implemented active control groups, has demonstrated improvements in divided attention/mental set-shifting (i.e., DTCs on a computerized divided attention task: Fraser et al., 2017; Bherer et al., 2021; Stroop switching reaction time: Desjardins-Crepeau et al., 2016).

Finally, we did not conduct any follow-up assessments after the intervention ended, limiting our understanding of the potential long-term effects of executive function training on brain activity while dual tasking. Specifically, it is unknown whether the pattern of neural compensation following executive function training would remain after the cessation of training or with ongoing strengthening of skills (i.e., from further training or greater uptake and implementation of executive function skills in everyday life). It could be speculated that the neural mechanism underlying dual-task performance might be altered over time, such that when executive function skills are first being acquired, a pattern of neural compensation might result, whereas once the skills become more engrained and practiced, this might lead to increased neural efficiency. This interpretation is drawn from the findings of Petersen et al. (1998) who demonstrated that a neural network, including prefrontal regions, was highly active during early stages of skill acquisition, but activity in the identified network decreased as performance became more skilled. Further research investigating the long-term effects of cognitive training on the neural mechanisms underlying dual-task performance may help elucidate this interpretation.

Conclusions

This study aimed to explore the relationship between frontal brain activity and cognitive-motor dual-task performance following at-home executive function training, across middle-aged and older-adults. Our findings suggest a potential pattern of neural compensation following executive function training (i.e., higher frontal brain activity predicted lower cognitive and motor dual-task costs), particularly in individuals who demonstrated a higher magnitude of improvement on the trained tasks, in line with compensatory theories of cognitive aging (e.g., Reuter-Lorenz & Park, 2014). Individual differences factors (i.e., age, baseline cognitive performance) were also found to influence participants' capacity for neural up-regulation to benefit cognitive-motor dual-task. Our findings may also suggest a potential trade-off between cognitive and motor domains depending on the level of cognitive resources available to the individual, which may alter how the brain responds to support dual-task performance. For example, following training, neural compensation of gait was found in individuals with lower cognitive functioning, suggestive of postural prioritization (Li et al., 2001; Shumway-Cook et al., 1997), whereas neural compensation of cognition was found in participants with higher cognitive functioning, suggestive of a posture-second strategy. Ultimately, our results offer valuable insights into the potential neural mechanisms that may drive improvements in cognition and gait following executive function training, and how the brain may adapt differently depending on individual difference factors. Higher cognitive reserve at baseline or enhanced cognitive resources gained from executive function training may stimulate compensatory scaffolding to support dual-task performance in middle-aged and older adults. Future research may consider exploring the potential long-term effects of executive function training on neural adaptations while dual tasking.

Postscript

The results from Studies 1 and 2 demonstrated interesting, but conflicting findings regarding the effect of baseline cognitive functioning on training efficacy in older adults. Specifically, Study 1 revealed that lower baseline cognitive functioning was associated with greater improvements in cognitive DTCs following cognitive training or physical exercise. In contrast, Study 2 demonstrated that following EF training, higher baseline cognitive functioning predicted greater improvements in cognitive DTCs, whereas lower baseline cognition predicted a greater reduction in gait DTCs. As such, we wanted to further explore the potential impact of baseline cognitive functioning on dual-task outcomes following training in a sample of older adults who already presented with cognitive difficulties (i.e., MCI).

In line with this individual-differences approach, we were also motivated by research on the intersection between auditory, cognitive, and motor functioning in late adulthood. While there is mounting evidence to suggest the increased cognitive involvement in hearing and mobility with age, there is relatively limited research examining the effect of hearing ability on cognitive-motor dual-task outcomes following training. We initially aimed to examine whether hearing loss moderated neuroplastic changes in dual-task performance following EF training (i.e., in Study 2), but due to our small and unequal sample size, we opted to focus on differences across middle-aged and older adults instead. The protocol for the randomized controlled trial, including a detailed description of our study participants, measures, and rationale is included in Appendix B. Additionally, exploratory analyses examining cognitive-motor dual-task performance and brain activity before and after executive function training across older adults with normal hearing and hearing loss is included in Appendix C. To continue this line of questioning, in our final study (Study 3), we explored the impact of hearing ability (including both clinical and sub clinical hearing loss) on cognitive-motor dual-task performance following exercise, alone or in combination with EF training in MCI participants.

CHAPTER FOUR:

Study 3

The Effect of Hearing Ability on Dual-Task Performance Following Multi-Domain Training in Older Adults with Mild Cognitive Impairment: Findings from the SYNERGIC Trial

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Manuscript prepared to be submitted to Frontiers in Aging Neuroscience. Minor changes to formatting and citation style were made to make the manuscript more cohesive with the rest of the dissertation.

Abstract

Background: Hearing loss is one of the largest potentially modifiable risk factors for dementia and is linked with poor cognitive-motor dual-task performance (e.g., walking while performing a cognitive task). Hearing loss is more prevalent and severe in males, whereas dementia is more prevalent in females. Physical exercise and cognitive interventions appear promising in improving dual -tasking in older adults; however, it is currently unclear whether hearing ability affects training efficacy on dual-task outcomes in older adults with mild cognitive impairment (MCI), and whether sex influences this effect.

Objective: This study examined whether hearing ability affects dual-task performance before and after physical exercise, alone or combined with cognitive training, in individuals with MCI. We also explored whether sex moderates this effect.

Methods: Secondary data was analysed from 75 participants with MCI (M_{age} = 73.66 ± 6.67) enrolled in the SYNERGIC trial. Hearing ability was assessed using self-report and behavioural measures. Participants completed a 20-week intervention: 1) Exercise (aerobic-resistance exercise + sham cognitive training; n = 31), 2) Multi-Domain Training (aerobic-resistance exercise + cognitive training; n = 32), or 3) Placebo Training (balance and toning exercises + sham cognitive training; n = 12). Primary outcomes included dual-task gait and cognitive performance.

Results: At baseline, poorer hearing predicted worse dual-task performance, particularly in males. Dual-task gait variability significantly improved following Multi-Domain Training in participants with a greater degree of self-reported hearing complaints. Sex-stratified analyses revealed that females with more hearing complaints improved more across all interventions, while in the Multi-Domain group, males with poorer objective hearing and females with better hearing showed the greatest gains. Additionally, in those with poorer hearing, lower cognitive scores (MoCA) predicted greater improvements after Multi-Domain Training, but a decline after Placebo Training.

Conclusions: Hearing ability, sex, and cognitive status appear to interact to influence the effects of exercise and cognitive training on dual-task performance in older adults with MCI. Multi-Domain Training appears particularly beneficial for those with hearing loss (who are male and/or have lower cognitive status), highlighting the need for personalized interventions to preserve function and slow decline in this at-risk population.

Trial Registration: Identifier: NCT02808676.
https://www.clinicaltrials.gov/ct2/show/NCT02808676

Key words: mild cognitive impairment, hearing loss; dual-task; gait; exercise; cognitive training; multi-domain training

Introduction

Background

Between 16 to 22% of older adults over the age of 65 have mild cognitive impairment (MCI; Manly et al., 2022; Roberts & Knopman, 2013). MCI is considered a transitional state between age-normative cognitive functioning and dementia, with annual conversion rates of MCI to dementia ranging between 10 to 15% (Petersen, 2004; Roberts & Knopman, 2013). While research demonstrates that females have a greater risk of developing dementia compared to males (Cao et al., 2020), there is mixed evidence for sex differences in MCI (Au et al., 2017). In addition to cognitive impairment, individuals with MCI also commonly experience deficits in gait and balance (Bahureksa et al., 2016) and are at an increased risk for falls (Liu-Ambrose et al., 2008). Cognitive-motor dual tasking (i.e., simultaneous completion of a cognitive and motor task) is a sensitive marker of cognitive and physical decline in older adults (Beauchet et al., 2009; Ramírez & Gutiérrez, 2021). Indeed, studies have shown that older adults with MCI have slower and more variable gait during dual tasking, compared to cognitively unimpaired older adults (Montero-Odasso et al., 2012a; Muir et al., 2012). Targeting this early prodromal stage of dementia is widely considered the optimal stage for intervention to slow the progression of decline (Peterson, 2004).

Non-pharmacological interventions have been shown to improve cognitive functioning in cognitively unimpaired older adults, as well as older adults with MCI or dementia, including aerobic exercise and resistance training (Falck et al., 2019; Huang et al., 2022) and computerized cognitive training (Chan et al., 2024; Hill et al., 2017; Zhang et al., 2019). There is also evidence that physical exercise and executive function training can improve cognitive-motor dual-task performance in cognitively unimpaired older adults, such as dual-task auditory working memory performance (Downey et al., 2022), postural control (Fraser et al., 2017; Li et al., 2010; Smith-Ray et al., 2015) and gait (Fraser et al., 2017; Marusic et al., 2018; Plummer et al., 2015). There is currently mixed evidence for the potential synergistic effect of combined physical exercise and computerized cognitive training, with some studies demonstrating improvements to global cognition (Montero-Odasso et al., 2023) and cognitive dual-task performance (Bherer et al., 2021), while others show no synergistic benefit (e.g., Desjardins-Crepeau et al., 2016; Fraser et al., 2017). As such, further research into the potential synergistic benefits of physical exercise and cognitive training on dual-task performance in older adults with MCI is needed.

In addition to cognitive and physical decline, hearing loss is also highly prevalent in late adulthood, affecting up to two-thirds of older adults over the age of 70 (Lin et al., 2011). Sex differences have also been found in age-related hearing loss, with hearing loss being more common, more severe, and having an earlier onset in males compared to females (Nolan, 2020). Hearing loss has been identified as one of the largest potentially modifiable risk factors for dementia (Livingston et al., 2017; 2020; 2024). Additionally, cognitive-motor dual-task performance has been found to differ across participants with normal hearing and hearing loss. Specifically, compared to older adults with normal hearing, older adults with hearing loss have been shown to have reduced auditory working memory performance when simultaneously engaged in a postural control task (Bruce et al., 2019a), and higher dual-task costs in gait speed and cadence (Wollesen et al., 2018). Hearing loss is also associated with postural instability and an increased risk of falling in older adults (Agmon et al., 2017; Campos et al., 2018; Carpenter & Campos, 2020; Foster et al., 2022). These findings thus highlight the complex interplay between cognitive, auditory, and motor systems with age. Research into this growing population with comorbid hearing loss and MCI is needed to better understand approaches to maintain functional capacity and reduce cognitive and physical decline. While interventions to improve cognitive and physical functioning in older adults with MCI appear promising, less is known about how hearing loss may impact training efficacy.

According to compensatory theories of cognitive aging, physical exercise and cognitive training may enhance neural scaffolding, or the engagement/upregulation of supplementary neural activity to counteract age-related neurofunctional decline (Reuter-Lorenz & Park, 2014). Li et al. (2018) further proposed that compensatory scaffolding not only assists in preserving cognitive functioning in the aging brain, but also sensory and motor functioning, such as cognitive-motor dual tasking. It has been postulated that in individuals with hearing loss, auditory deprivation over time leads to structural and functional brain changes, such as temporal lobe atrophy and the re-allocation of cognitive resources to support auditory processing (Lin et al., 2014; Peelle & Wingfield, 2015; Powell et al., 2022). As such, physical exercise and cognitive training may enhance compensatory scaffolding, and in turn, dual-task performance, and these benefits may extend to individuals with MCI and poorer hearing who may have alterations in brain structure and function caused by reduced auditory processing over time.

Taken together, there is moderate evidence for the efficacy of physical exercise and cognitive interventions to improve dual-task performance in older adults, with mixed evidence for a potential synergistic effect of combined physical exercise and cognitive training. However, there have yet to be any investigations into the effects of hearing ability on dual-task outcomes in older adults with MCI before and after physical exercise and cognitive training. Additionally, while there are known sex differences in the prevalence rates of dementia and hearing loss in older adults, it is currently unknown whether biological sex influences the relationship between hearing loss severity and dual-task performance in older adults with MCI before and after training.

Research objectives and hypotheses. By utilizing a subset of data from the SYNnchronizing Exercises, Remedies in Gait and Cognition (SYNERGIC) trial (Identifier: NCT02808676; i.e., including participants who were co-enrolled in a longitudinal study that included a hearing evaluation), the primary objectives of this study were to determine whether hearing ability predicts cognitive-motor dual-task performance at baseline, and if degree of hearing loss predicts training-related improvements in dual-task performance following physical exercise, alone or in combination with cognitive training. We were also interested in exploring whether any sex differences would emerge for each research objective. We hypothesized that with increasing severity of hearing loss, there would be poorer cognitive and gait dual-task performance at baseline, and a higher magnitude of improvement in dual-task performance following Multi-Domain Training and Exercise Training, with the greatest magnitude of improvement following Multi-Domain Training. Additionally, given that males tend to experience a greater severity of hearing loss compared to females, we further hypothesized that the relationship between hearing ability and dual-task performance would be stronger in males compared to females at baseline, and that males with a greater degree of hearing loss would improve more following training.

Methods

Participants

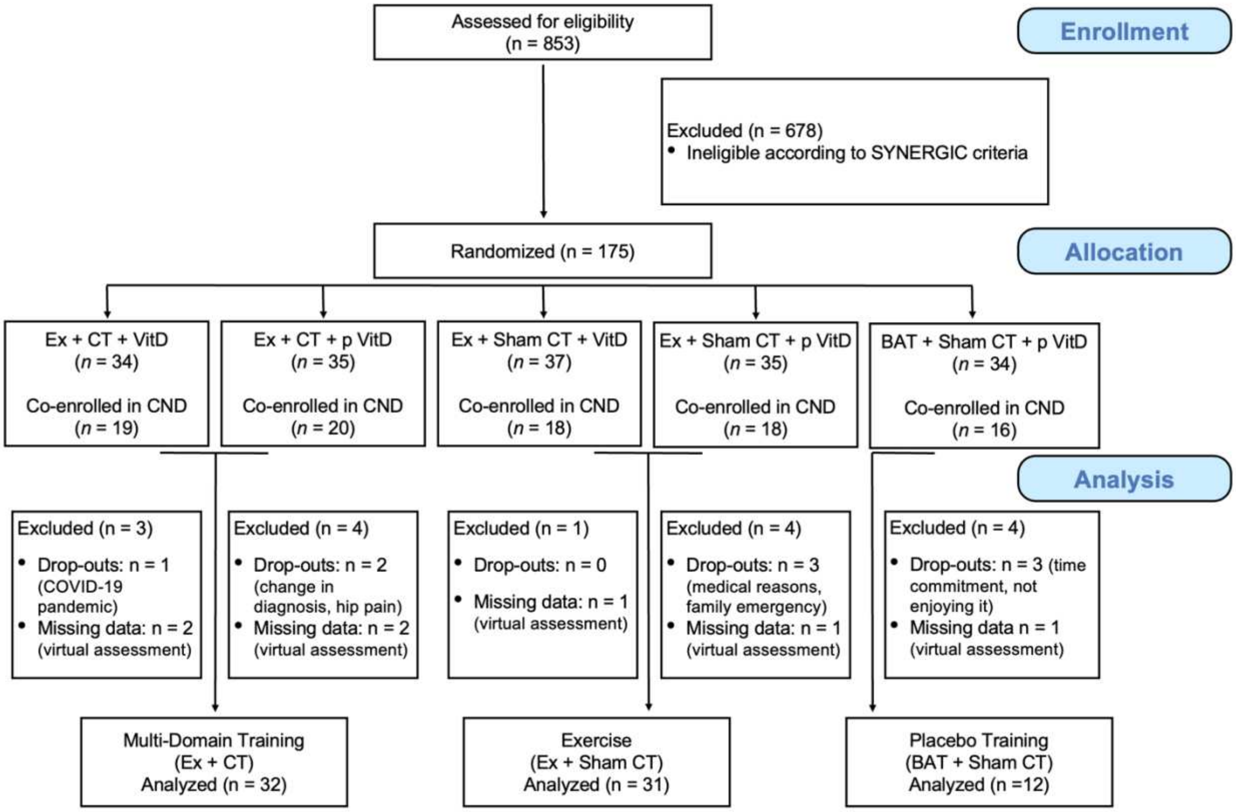
Participants were comprised of a subset of individuals with MCI from the SYNERGIC trial who were co-enrolled in a longitudinal study that included a hearing evaluation (i.e., Comprehensive Assessment of Neurodegeneration and Dementia; COMPASS-ND), which was carried out under the auspices of the Canadian Consortium on Neurodegeneration and Aging (CCNA). Participants were included in the current analyses if they were between 60 and 85 years old and had a diagnosis of MCI (i.e., cognitive impairment in one of the following four cognitive domains: memory, executive function, attention, and language, with preserved activities of daily living and absence of dementia). Participants were excluded if they had an uncontrolled psychiatric disorder, a neurological disorder with residual motor deficits, uncontrolled hypertension, diabetes, known renal/kidney insufficiency, or were actively participating in another physical exercise program and/or clinical trial. There were no exclusion criteria based upon hearing ability (i.e., participants were not excluded if they were diagnosed with a hearing impairment or if they wore hearing aids). Full details concerning recruitment and eligibility are described elsewhere (Chertkow et al., 2019; Montero-Odasso et al., 2018; 2023).

The SYNERGIC trial aimed to recruit a total of 200 participants (40 per training group) to investigate the effect of physical exercise, alone or in combination with cognitive training, and Vitamin D_3 supplementation on global cognition (Montero-Odasso et al., 2018; 2023). The sample size calculation for the current set of analyses was based upon results from Fraser et al. (2017), who used a similar physical exercise and executive function training protocol with different combinations of active and control conditions and reported pre- and post-training changes in our primary outcome measures (i.e., dual-task gait, auditory working memory) in cognitively healthy older adults. In order to achieve a power of .95 at an alpha level of .05 for a main effect of Time (pre- vs. post-training) for cognitive accuracy, the recommended sample size was 30 participants total (i.e., 10 participants per training group).

A total of 853 participants were screened for eligibility to participate in the SYNERGIC study. Following screening procedures, 175 participants were deemed eligible and were randomized to one of five treatment arms (see Interventions section for full description of the intervention arms). Of note, results from Montero-Odasso et al. (2023) revealed no significant differences between Vitamin D supplementation versus placebo on cognitive performance and so we pooled the data across the Vitamin D groups. Of the 175 participants, 90 were co-enrolled in the COMPASS-ND study. Of these 90 participants, 15 participants were excluded from the analyses (9 withdrew, 6 had missing data due to the COVID-19 pandemic). Therefore, a total of 75 participants (M_{age} = 73.66 years ± 6.67) were included in the study analyses: 32 in the Multi-Domain Training group, 31 in the Exercise group, and 12 in the Placebo Training group (See Figure 1 for CONSORT flow diagram, and Table 1 for participants characteristics across training groups).

Figure 1

Consort Flow Diagram of Participant Recruitment and Group Allocation



Note. Ex = Aerobic-resistance exercise; CT = Cognitive training; BAT = Balance and toning; VitD = Vitamin D_3; p = Placebo; CND = COMPASS-ND. Results from Montero-Odasso et al. (2023) and the current set of analyses did not reveal any significant differences between Vitamin D_3 supplementation versus placebo on our primary outcome measures. We therefore pooled the data across the Vitamin D groups to increase statistical power, leading to a total of three treatment arms.

Measures

Demographics and background measures. Demographic information was collected during a screening visit for the SYNERGIC trial. In the current study, we included the participants' self-reported age, sex, years of education, and hearing aid use. Global cognitive functioning was measured with the Montreal Cognitive Assessment (MoCA; total score out of 30; Nasreddine et al., 2005). Hearing ability was assessed in the COMPASS-ND study using a self-report questionnaire and two behavioural measures. Specifically, participants completed the Hearing Handicap Inventory for The Elderly - Screening Version (HHIE-S; total score of 40; Ventry & Weinstein, 1983), a 10-item questionnaire designed to evaluate the emotional and social impacts of hearing loss, with higher scores indicating a greater disability associated with hearing loss. An abbreviated pure-tone audiometry assessment was conducted as a screening procedure. Participants were assigned to one of two hearing loss categories based on their ability to detect 2-kHz pure tones. Supplementary analyses were conducted using this measure to examine the effect of hearing status (defined categorically as impaired or unimpaired) on dual-task performance before and after Multi-Domain Training, Exercise, or Control. The methodology on the abbreviated pure-tone audiometry assessment is included in the Supplementary Material. Additionally, the descriptive statistics for the participant characteristics across hearing categories is listed in Supplementary Table 1. The Canadian Digit Triplet Test (CDTT; Giguère et al., 2020) was administered to examine suprathreshold hearing abilities in noise and was the primary behavioural measure of hearing loss included in the study analyses. The test was administered in a quiet office using a laptop, a pair of headphones (DD45), and a response keypad. For each of 24 trials, participants heard a set of three digits presented amongst background noise. Participants were instructed to enter the digits heard in order on each trial using a touch-tone phone keypad. The level of noise presented on each trial was adjusted using an automated adaptive procedure. The outcome variable of interest was the speech reception threshold (SRT) in noise, which was computed through the CDTT's adaptive scoring procedure. The SRT corresponds to the signal-to-noise ratio (SNR) at which the triplets are correctly recognized 50% of the time.

Primary outcome measures. As part of the SYNERGIC trial, single- and dual-task performances were evaluated using three different cognitive tasks involving working memory and updating (i.e., Serial 1 and 7 Subtractions) and Semantic Fluency (i.e., naming animals). For the Serial Subtraction conditions, participants were given a random three-digit number and instructed to continuously subtract either one or seven from their answer out loud. Responses following the starting number were recorded for accuracy. If the participant made an error, subsequent correct subtractions were considered accurate (e.g., if the starting number was 100 and the participant responded 93, 87, 80, they would receive an accuracy score of 2). For the semantic fluency condition, participants were asked to generate as many animals as they could think of out loud. Responses were recorded to obtain a measure of accuracy (i.e., total number of responses minus repetitive and intrusion errors). The single-task cognitive conditions (i.e., Serial 7 Subtractions, Semantic Fluency) were completed while seated and participants were given 10 seconds to complete each of the cognitive tasks. The dual-task cognitive conditions (Serial 1 And 7 Subtractions, Semantic Fluency) involved the simultaneous completion of the cognitive tasks while walking (more details below). Participants first completed the single-task cognitive trials before the gait and dual-task assessments were completed. The amount of time participants had to complete each cognitive dual-task depended on how quickly the walking task was completed.

To account for differences in the time to complete each task, an accuracy divided by time score was calculated for each single- and dual-task condition.

The gait task involved walking at a usual pace along a 6-meter gait mat (ProtoKinetic®, GAITRite® Systems, Inc.). To account for acceleration and deceleration of gait, participants were instructed to start walking one meter before the gait mat and end walking one meter beyond the gait mat (Cullen et al., 2018). Single task walking trials were completed three times. Under dual-task conditions, participants walked along the gait mat once for each of the three cognitive tasks. The gait mat allowed for the measurement of spatiotemporal gait characteristics using embedded electronic pressure sensors. Gait parameters included gait speed (cm/s), stride time (ms; i.e., time elapsed between the first contact of two consecutive footsteps of the same foot), stride length (cm; i.e., distance between successive points of initial contact of the same foot), and double-support time (ms; portion of stride time in which both feet are on the ground). In addition to mean performance calculated across multiple gait cycles, the coefficient of variation (CV = (standard deviation / mean) × 100) was also calculated for each of these measures to quantify gait variability. Additionally, proportional dual-task costs were calculated as follows: ((single-task – dual-task)/single-task)*100.

Study Procedures

The hearing assessments were conducted in an initial screening visit in the COMPASS-ND study, and the dual-task experiment was conducted in the SYNERGIC trial. Participants completed 20 weeks of training, which was followed by the same dual-task assessment post-training. Data were stored and accessed from the Longitudinal Online Research and Imaging System (LORIS) database (Mohaddes et al., 2012). Refer to Chertkow et al. (2019) for the complete COMPASS-ND study protocol, as well as Montero-Odasso et al. (2018; 2023) and

Bray et al. (2023a) for the SYNERGIC study protocol. The COMPASS-ND study was approved by the Jewish General Hospital Research Ethics Board. For the SYNERGIC study, all procedures were approved by the Research Ethics Board at the University of Western Ontario (REB# 107670), the Lawson Health Research Institute's Clinical Research Impact Committee (R-15-038), and Health Canada (HC file-HC6–24-c195918 / HC protocol #201619). Each intervention site also obtained local ethical approval. Finally, study procedures, including retrospective data analyses, were approved by Concordia University's Human Research Ethics Committee (Certificate #30014926). All participants provided informed consent.

Interventions

Participants were randomized to one of five treatment arms, involving both active and control interventions, including (1) Aerobic-resistance exercise (Ex) + Cognitive Training (CT) + Vitamin D_3, (2) Ex + CT + Vitamin D placebo, (3) Ex + Sham CT + Vitamin D_3, (4) Ex + Sham CT + Vitamin D placebo, and (5) Balance and Toning (BAT) exercises + Sham CT + Vitamin D placebo. As previously noted, results from Montero-Odasso et al. (2023) and the current set of analyses revealed no significant differences between Vitamin D supplementation versus placebo on cognitive and dual-task outcomes. We therefore pooled the data across the Vitamin D groups, leading to a total of three treatment arms: (1) Multi-Domain Training: Ex + CT (2) Exercise: Ex + Sham CT, and (3) Placebo Training: BAT + Sham CT. Interventions were completed in small groups (up to eight participants) three times a week for 20 weeks. Each session lasted approximately 90 minutes, with 30 minutes devoted to the cognitive training or cognitive sham program, followed by 60 minutes of active physical exercise or the placebo BAT exercises (see Montero-Odasso et al., 2018, 2023 for further details).

Physical exercise interventions. The active physical exercise intervention involved upper and lower body resistance training, as well as aerobic exercise (e.g., walking, cycle ergometers). Intensity of physical exercise was monitored using the Borg Rating of Perceived Exertion (Borg, 1982), which progressed for the aerobic exercise component throughout the training every four weeks. The placebo physical exercise intervention (BAT) was designed to improve muscle tone and flexibility (e.g., stretching, balance, toning exercises), without improving strength or aerobic capacity. The control exercises did not progress in volume or intensity.

Cognitive interventions. The cognitive intervention (Neuropeak) was completed on individual tablets (iPad®) and involved dual-task training aimed at improving divided attention (i.e., sharing attention between two simultaneous tasks). The cognitive exercises progressed in difficulty across the 20 weeks of training. Specifically, the first 30 training sessions were performed following a fixed priority instruction (during dual-task trials, participants were asked to keep an equal priority across tasks). The following 30 sessions were performed following a variable priority instruction (during dual-task trials, participants were instructed to prioritize one task over the other, which varied across blocks). In the sham cognitive training condition, participants completed two different tasks (i.e., internet searching and video watching), which alternated across sessions, using the same tablet (iPad®) as the cognitive training group. The duration of time to complete the tasks was the same as the cognitive training.

Statistical Analyses

Results were obtained through a secondary data analysis from participants co-enrolled in the SYNERGIC and COMPASS-ND studies, across two time-points from the SYNERGIC study (baseline and post-training). All data processing and analyses were completed using Rstudio version 4.2.3 (Posit team, 2023). Descriptive statistics were carried out for each variable at each assessment timepoint. Outliers were identified using the boxplot method (i.e., values above the third quartile or below the first quartile range) and corrected using Winsorization (i.e., outliers were replaced with the next most extreme value). Each outcome measure was normally distributed (skew indices ranging from -.20 to .47), though were mildly leptokurtic (kurtosis values ranged from 2.12 – 2.55). No transformations were computed since one of the primary goals of our analysis was to compare groups and assess changes over time. Transforming the data could lead to altered group distributions and relationships between variables, potentially distorting the natural structure of the data. By not transforming, we ensure that the comparisons across groups and time points remain valid and reflect the true underlying differences or trends present in the raw data. Group mean centering of continuous variables was conducted to improve accuracy of slope variance estimates and interpretation of main effects and interactions.

Chi square tests (for categorical variables) and one-way ANOVAs (for continuous variables) were conducted to determine if there were any differences between training groups at baseline. Bivariate correlations were conducted to determine if there were any associations between hearing measures and participants' characteristics at baseline. Additionally, chi square tests and independent sample t-tests were conducted to determine if there were any significant differences in participant characteristics between males and females at baseline.

Separate linear mixed-effect models (LMM) were fitted for each of our outcome measures (i.e., gait speed, stride time, stride time variability, stride length, stride length variability, double-support time, cognitive accuracy) using the *lmer* (Bates et al., 2014) and *lmerTest* packages. The parsimonious model selection procedure (Bates et al., 2015) using a backwards elimination approach was utilized. The initial LMM included fixed effects for HHIE scores, CDTT SRTs, Task (single-task, dual-task), Condition (S1 Subtraction, S7 Subtraction, Semantic Fluency), Intervention (Multi-domain Training, Exercise, Placebo Training), Time (pre-, post-training), Age, Sex (male/female), Education, MoCA scores, and their interactions. Random intercepts, including the within-subject differences across testing sites, were included as a nested factor. Models were optimized based on LMM's goodness of fit using the likelihood ratio test. Fixed effects and interactions that did not reliably contribute to model fit were removed, except for confounds (i.e., age, sex, education) to be consistent with previous literature, as well as instances where the fixed effects or interactions were necessary to evaluate our proposed research question (e.g., three-way interaction between hearing measures, intervention, and time). See Supplementary Material for detailed model fit estimates.

Once the best fitting models were determined, *Estimates* and *p-values* were calculated from the *lmer* package (Bates et al., 2014) for continuous independent variables, and omnibus *F*- and *p*-values were calculated using the *Anova* function from the *car* package (Fox & Weisberg, 2019) for categorical independent variables. Kenward-Roger's method was used to estimate degrees of freedom (Halekoh & Højsgaard, 2014). For the analyses involving continuous independent variables, relative effect sizes (i.e., proportion of variance explained by the given effect relative to the proportion of outcome variance unexplained) were computed as f^2 following Aiken and West guidelines (1991), where an effect size of 0.02 is considered small, 0.15 is considered medium, and 0.35 is considered large (Cohen, 1992). For our analyses involving categorical independent variables, effect sizes were computed as η_p^2, where a value of 0.01 indicates a small effect, .06 indicates a medium effect, and .14 indicates a large effect. Observation of statistically significant main effects or interactions were followed up by post hoc pairwise analyses with Bonferroni correction using the *emmeans* package (Lenth, 2023).

Contrasts involving continuous variables were estimated using the *emtrends* function from the *emmeans* package.

Results

Baseline Data Inspection

Descriptive statistics and between-group analyses for the intervention arms and sex are shown for all background measures in Tables 1 and 2, respectively. We did not find any significant differences across intervention arms or males and females for any of the background measures, with the exception of a significant difference in MoCA scores across training groups (Table 1). Post-hoc pairwise analyses showed that MoCA scores were marginally higher at baseline in the Multi-Domain group compared to the Placebo Training group, although this did not reach significance ($p = .05$). Nevertheless, MoCA performance was included as a covariate in all the linear mixed models.

In examining whether there were any associations between our hearing measures and participant characteristics at baseline, we found a significant positive correlation between CDTT SRTs and Age ($r = .347$, $p < .05$), and a significant negative correlation between CDTT SRTs and MoCA scores ($r = -.553$, $p < .001$) such that hearing performance was worse (i.e., higher CDTT SRTs) in participants with lower MoCA scores and older age. There was also a significant positive correlation between HHIE-S scores and CDTT SRTs ($r = .569$, $p < .001$), such that a greater degree of self-reported hearing complaints (i.e., higher HHIE-S scores) was associated with poorer objective hearing performance (i.e., higher CDTT SRTs). Notably, the correlation between HHIE-S and CDTT SRTs differed across males ($r = .720$, $p < .001$) and females ($r = .366$, $p = .094$), such that greater hearing complaints (i.e., higher HHIE-S scores) were only associated with poorer hearing performance (i.e., higher CDTT SRTs) in male participants.

Table 1

Means, Standard Deviations, and One-Way ANOVAs/Chi Square Tests for Participant Characteristics Across Training Groups at Baseline

Measure	Multi-Domain Training n = 32		Exercise n = 31		Placebo Training n = 12		*F or* χ^2	*p*	η^2
	M	*SD*	*M*	*SD*	*M*	*SD*			
Age (years)	72.59	7.60	74.65	6.24	73.92	5.71	.730	.486	.020
Education (years)	15.34	2.86	15.32	3.87	17.71	6.01	1.86	.163	.049
MoCA (/30)	23.97	2.90	22.48	2.72	21.58	3.18	3.78*	.027	.095
HHIE-S (/40)	9.63	10.28	7.23	7.71	7.82	8.69	.576	.565	.016
CDTT SRT (SNR)	-8.94	3.72	-9.03	3.13	-8.10	5.85	.184	.833	.007
Sex (*n*, % female)	14 (43.75)		10 (32.26)		8 (66.67)		4.21	.122	
Hearing aid use (*n*)	5		3		1		1.75	.417	

Note. Multi-domain training consisted of aerobic-resistance exercise with cognitive training; Exercise consisted of aerobic-resistance exercise with sham cognitive training; Placebo training consisted of balance and toning exercises with sham cognitive training; MoCA = Montreal Cognitive Assessment; HHIE-S = Hearing Handicap Inventory for The Elderly - Screening Version; CDTT SRT = Canadian Digit Triplet Test – Speech Response Threshold; SNR = Signal to noise ratio; * $p < .05$.

Table 2

Descriptive Statistics and Independent Sample T-Tests/Chi Square Tests for Participant Characteristics and Hearing Measures Across Males and Females at Baseline

Variable	Males			Females			*t or* χ^2	*p*	*d*
	n	*M*	*SD*	*n*	*M*	*SD*			
Age (years)	43	74.07	6.72	32	73.09	6.88	.616	.540	.144
Education (years)	43	16.07	4.57	32	15.23	2.92	.904	.369	.211
MoCA (/30)	43	22.63	2.82	32	23.44	3.16	-1.17	.247	-.270
HHIE-S (/40)	43	9.07	9.31	31	7.35	8.59	.807	.422	.190
CDTT SRT (SNR)	30	-8.38	3.73	23	-9.48	3.89	1.04	.302	.289
Hearing Aid (*n*)		7			5		4.21	.122	

Note. MoCA = Montreal Cognitive Assessment; HHIE-S = Hearing Handicap Inventory for The Elderly - Screening Version; CDTT SRT = Canadian Digit Triplet Test – Speech Response Threshold; SNR = Signal to noise ratio.

Effect of Hearing Ability on Single- and Dual-Task Gait Performance at Baseline

In examining the effect of hearing ability on dual-task gait performance at baseline, we found significant effects of HHIE-S scores (i.e., self-reported hearing complaints) on temporal aspects of gait, gait stability, as well as gait DTCs (Table 3). Specifically, participants with greater hearing complaints (i.e., higher HHIE scores) had longer stride times, higher stride length variability, and higher DTCs for gait speed, stride time, and stride length variability. Similarly with the behavioural hearing data, we found significant effects of CDTT, such that participants with poorer objective hearing (i.e., higher CDTT SRTs) had slower gait speed, longer stride times, longer double-support time, and higher DTCs for gait speed, and double-support time (Table 3). We did not find any significant effects of hearing ability (measured with both self-report and behavioural testing) on single-task gait performance.

Effect of Hearing Ability on Gait Performance at Baseline: Interactions with Cognitive Status

Given the observed associations between hearing ability and dual-task gait, we then asked whether the severity of cognitive impairment would have an additional detrimental effect on dual tasking. We found significant interaction effects of HHIE-S with MoCA scores for dual-task stride time and stride length variability, as well as DTCs for gait speed, stride time, and stride length variability (Table 3). Specifically, in participants with greater hearing complaints (i.e., higher HHIE-S scores), lower MoCA predicted poorer dual-task gait performance. Similarly, with the behavioural hearing data we found significant CDTT by MoCA interaction effects for dual-task gait speed, stride time, stride length variability, and double-support time, as well as DTCs for gait speed and double-support time (Table 3). Specifically, in participants with poorer hearing performance (i.e., higher CDTT SRTs), lower MoCA scores predicted poorer dual-task gait performance.

Table 3

Linear Mixed Models for all Participants with Hearing Measures and MoCA Included as Fixed Effects and Dual-Task Gait Performance as Dependent Variables

Dependent Variable	**Fixed Effects**	***t (df)***	***β***	***SE***	***p***	f^2
Gait speed (cm/s)	CDTT	-2.54 (45)	-40.98	16.12	.010	.09
	CDTT*MoCA	2.50 (45)	1.76	.70	.016	.15
Gait speed DTC (%)	HHIE	2.56 (63)	3.37	1.37	.017	.05
	HHIE*MoCA	-2.44 (63)	-.014	.06	.018	.08
	CDTT	2.35 (45)	15.28	6.51	.010	.07
	CDTT*MoCA	-2.25 (45)	-.64	.28	.030	.08
Stride time (ms)	HHIE	2.29 (63)	43.20	18.84	.025	.07
	HHIE*MoCA	-2.39 (63)	-1.95	.81	.020	.09
	CDTT	3.14 (45)	268.99	85.80	.003	.13
	CDTT*MoCA	-3.13 (45)	-11.75	3.75	.003	.15
Stride time DTC (%)	HHIE	2.72 (63)	2.51	.92	.009	.06
	HHIE*MoCA	-2.76 (63)	-.11	.04	.008	.09
Stride length variability (CoV%)	HHIE	2.35 (63)	.39	.17	.022	.03
	HHIE*MoCA	-2.27 (63)	-.02	.01	.026	.07
	CDTT*MoCA	-2.22 (43)	-.06	.03	.030	.12
Stride length variability DTC (%)	HHIE	2.78 (65)	17.16	6.17	.007	.05
	HHIE*MoCA	-2.65 (63)	-.70	.27	.010	.07
Double-support time (ms)	CDTT	2.23 (43)	105.62	46.83	.029	.10
	CDTT*MoCA	-2.21 (43)	4.52	2.05	.030	.18
Double-support time DTC (%)	CDTT	2.21 (43)	21.27	9.64	.033	.07
	CDTT*MoCA	-2.04 (43)	-.86	.42	.048	.12

Note. f^2 = a measure of effect size indicating the proportion of variance explained by the given effect relative to the proportion of outcome variance unexplained; HHIE = Hearing Handicap Inventory for The Elderly – Screening Version; CDTT = Canadian Digit Triplet Test; MoCA = Montreal Cognitive Assessment. Other fixed effects included in the models were Age, Education, Sex, Dual-Task Condition (i.e., S1 and S7 subtractions, semantic fluency), and their interactions. Random effects included participant ID nested within the Training Site (i.e., Montreal, Western, University of British Columbia (UBC), Waterloo, Laurier).

Effect of Hearing Ability on Gait Performance at Baseline: Sex-Specific Interactions

Given the known sex differences in hearing loss, we also explored sex differences within our models and by stratifying by sex. We found significant main effects of HHIE-S scores, as well as HHIE-S and MoCA interactions for dual-task gait speed, stride time, and stride length variability, as well as the DTCs for gait speed, stride time, and stride length variability in males only (Table 4). Specifically, in male participants with greater hearing complaints (i.e., higher HHIE-S scores), dual-task gait performance was poorer, and there was a more negative effect of MoCA scores on gait performance (i.e., in males with more hearing complaints, lower cognitive status predicted poorer dual-task gait performance). Similarly, we found significant main effects of CDTT SRTs, as well as interaction effects between CDTT SRTs and MoCA scores on dual-task gait speed, stride time, and double-support time, as well as the DTCs for gait speed and double-support time in males only (Table 4). In males with poorer objective hearing performance (i.e., higher CDTT SRTs), gait performance was poorer, and there was a more negative effect of MoCA scores on gait performance. We did not find any significant effects of CDTT or HHIE-S on dual-task gait performance at baseline in females.

Table 4

Linear Mixed Models for Males, with Hearing Measures and MoCA Included as Fixed Effects and Dual-Task Gait Performance as Dependent Variables

Dependent Variable	**Fixed Effects**	***t (df)***	***β***	***SE***	***p***	***f^2***
Gait speed (cm/s)	HHIE	-2.36 (34)	-10.50	4.44	.020	.09
	HHIE*MoCA	2.33 (34)	.45	.19	.026	.15
	CDTT	-3.23 (34)	-60.71	18.83	.004	.19
	CDTT*MoCA	3.21 (34)	2.64	.82	.004	.29
Gait speed DTC (%)	HHIE	3.33 (34)	5.80	1.74	.002	.14
	HHIE*MoCA	-3.22 (34)	-.25	.08	.003	.16
	CDTT	2.43 (24)	22.96	9.45	.022	.11
	CDTT*MoCA	-2.38 (24)	-.98	.41	.030	.13
Stride time (ms)	HHIE	2.68 (34)	60.83	22.71	.011	.12
	HHIE*MoCA	-2.69 (34)	-2.67	.99	.011	.18
	CDTT	2.95 (24)	319.70	108.48	.007	.17
	CDTT*MoCA	-3.05 (24)	-14.47	4.74	.005	.22
Stride time DTC (%)	HHIE	3.67 (34)	4.15	1.13	<.001	.05
	HHIE*MoCA	-3.54 (34)	-.17	.05	.001	.08
Stride length variability (CoV%)	HHIE	3.04 (34)	.66	.22	.004	.12
	HHIE*MoCA	-2.78 (34)	-.03	.01	.009	.17
Stride length variability DTC (%)	HHIE	3.78 (34)	27.59	7.30	<.001	.15
	HHIE*MoCA	-3.45 (34)	-1.09	.32	.002	.17
Double-support time (ms)	CDTT	2.26 (22)	141.47	62.74	.030	.14
	CDTT*MoCA	-2.30 (22)	-6.32	2.74	.030	.21
Double-support time DTC (%)	CDTT	2.42 (22)	34.77	14.32	.025	.10
	CDTT*MoCA	-2.32 (22)	-1.45	.63	.030	.14

Note. f^2 = a measure of effect size indicating the proportion of variance explained by the given effect relative to the proportion of outcome variance unexplained; HHIE = Hearing Handicap Inventory for The Elderly- Screening Version; CDTT = Canadian Digit Triplet Test; MoCA = Montreal Cognitive Assessment. Other fixed effects included in the models were Age, Education, Sex, Dual-Task Condition (i.e., S1 and S7 subtractions, semantic fluency), and their interactions. Random effects included participant ID nested within the Training Site (i.e., Montreal, Western, UBC, Waterloo, Laurier).

Effect of Hearing Ability on Single- and Dual-Task Cognitive Accuracy at Baseline

In examining the effect of hearing ability on cognitive accuracy at baseline, we did not find any significant main effects of HHIE-S or CDTT, or any interactions with cognitive status. However, we found significant interaction effects between Sex and both behavioural and self-report hearing measures for single-task and dual-task performance. Specifically, in participants with fewer hearing complaints (i.e., lower HHIE-S scores), single-task cognitive accuracy was significantly lower in females (M = .41 corr/s, SE = .04), compared to males (M = 0.56 corr/s, SE = .04), $t(64) = -3.02$, $p = .004$, $\eta_p^2 = .10$. Similarly, in participants with better objective hearing performance (i.e., lower CDTT SRTs), dual-task cognitive accuracy was significantly lower in females (M = .67 corr/s, SE = .05), compared to males (M = .82 corr/s, SE = .06), $t(46) = -2.11$, $p = .04$, $\eta_p^2 = .14$. In contrast, in participants with a higher degree of perceived hearing loss (i.e., higher HHIE-S scores), dual-task cognitive accuracy was marginally lower in males (M = .74 corr/s, SE = .04) compared to females (M = .87 corr/s, SE = .05), $t(65) = 1.95$, $p = .056$, $\eta_p^2 = .07$. Moreover, when the analyses were stratified by sex, there was a significant main effect of CDTT SRTs on dual-task cognitive accuracy for males, $t(59) = -2.06$, $p = .04$, $f^2 = .02$, such that in males, poorer objective hearing performance (i.e., higher CDTT SRTs) predicted lower accuracy scores (β = -.07 corr/s, SE = .03). There was also a significant interaction effect of CDTT SRTs with Age on cognitive accuracy DTCs in males, $t(28) = 3.12$, $p = .004$, $f^2 = .14$, such that older age and a higher degree of hearing loss predicted higher cognitive DTCs (β = 1.76%, SE = .57).

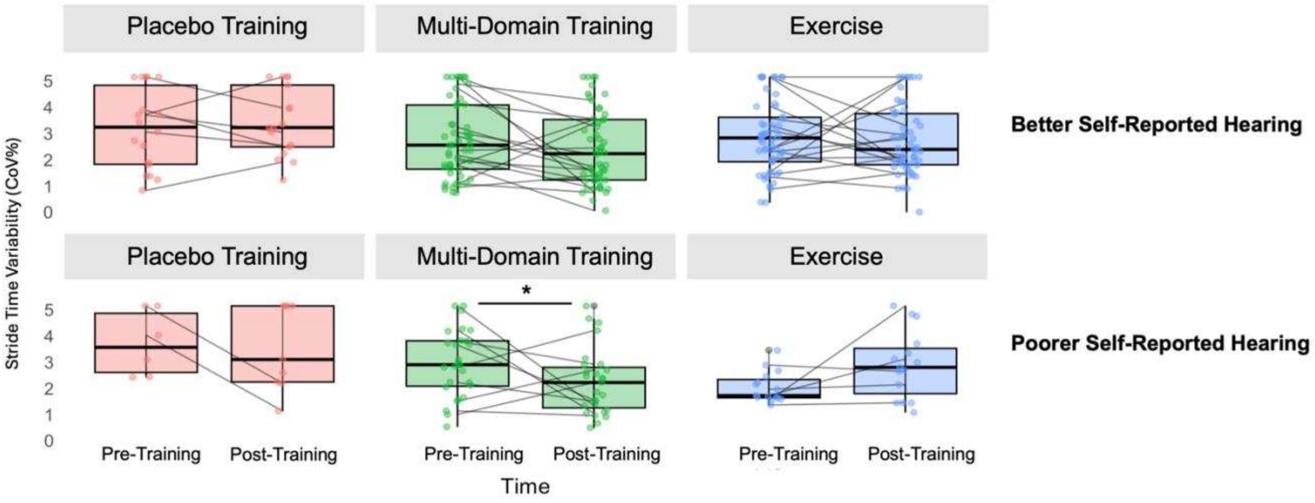
Effect of Hearing Ability on Single- and Dual-Task Performance from Pre- to Post-Training

In examining whether hearing ability predicted single- and dual-task performance from pre- to post-training (Research Question 2), we found a significant HHIE-S by Time by Training Group interaction effect for dual-task stride time variability, $F(2, 353) = 3.13$, $p = .045$, $\eta_p^2 = .02$.

Specifically, in participants with a greater degree of hearing complaints (i.e., higher HHIE-S scores), there was a significant reduction (i.e., improvement) in dual-task stride time variability only following Multi-Domain Training, $\Delta = -0.54$ % CoV, *SE* = .21, *p* = .01 (Figure 2). We did not find any significant interactions between hearing ability and change in single-task gait, single- and dual-task cognitive accuracy, or DTCs following training. Supplementary analyses examining hearing loss categorically using an abbreviated pure-tone audiometry assessment revealed similar results, such that dual-task stride time, stride time variability, and double-support time significantly improved in participants with hearing loss, but not in participants with normal hearing, regardless of training modality (i.e., Placebo Control, Multi-Domain, Exercise Training). Additionally, following Multi-Domain Training, dual-task stride length significantly improved in participants with hearing loss, and marginally improved in participants with normal hearing (see Supplementary Material).

Figure 2

Linear Mixed Model of HHIE by Time by Training Interaction Effect on Dual-Task Stride Time Variability



Note. Estimated marginal means of dual-task stride time variability (%CoV) following Placebo Training (balance and toning exercises + sham cognitive training), Multi-Domain Training (aerobic-resistance exercise + cognitive training), and Exercise (aerobic-resistance exercise + sham cognitive training) from pre- to post-training across participants with better self-reported hearing (top panel) and poorer self-reported hearing (bottom panel); The horizontal lines of the boxplots correspond to the 25th percentile, 50th percentile (median), and 75th percentile, respectively; The length of the box corresponds to the interquartile range (difference between 75th and 25th percentile); Each dot represents a data point for the serial 1 subtractions, serial 7 subtractions, and semantic fluency conditions for each participant; Lines connect data points (averaged across conditions) from pre- and post-training for each participant; Error bars correspond to the 95% confidence intervals of the estimated marginal means; HHIE-S = Hearing Handicap Inventory for The Elderly - Screening Version; Poorer self-reported hearing = HHIE-S scores greater than 1SD above the mean; Better self-reported hearing = HHIE-S scores less than 1SD below the mean.

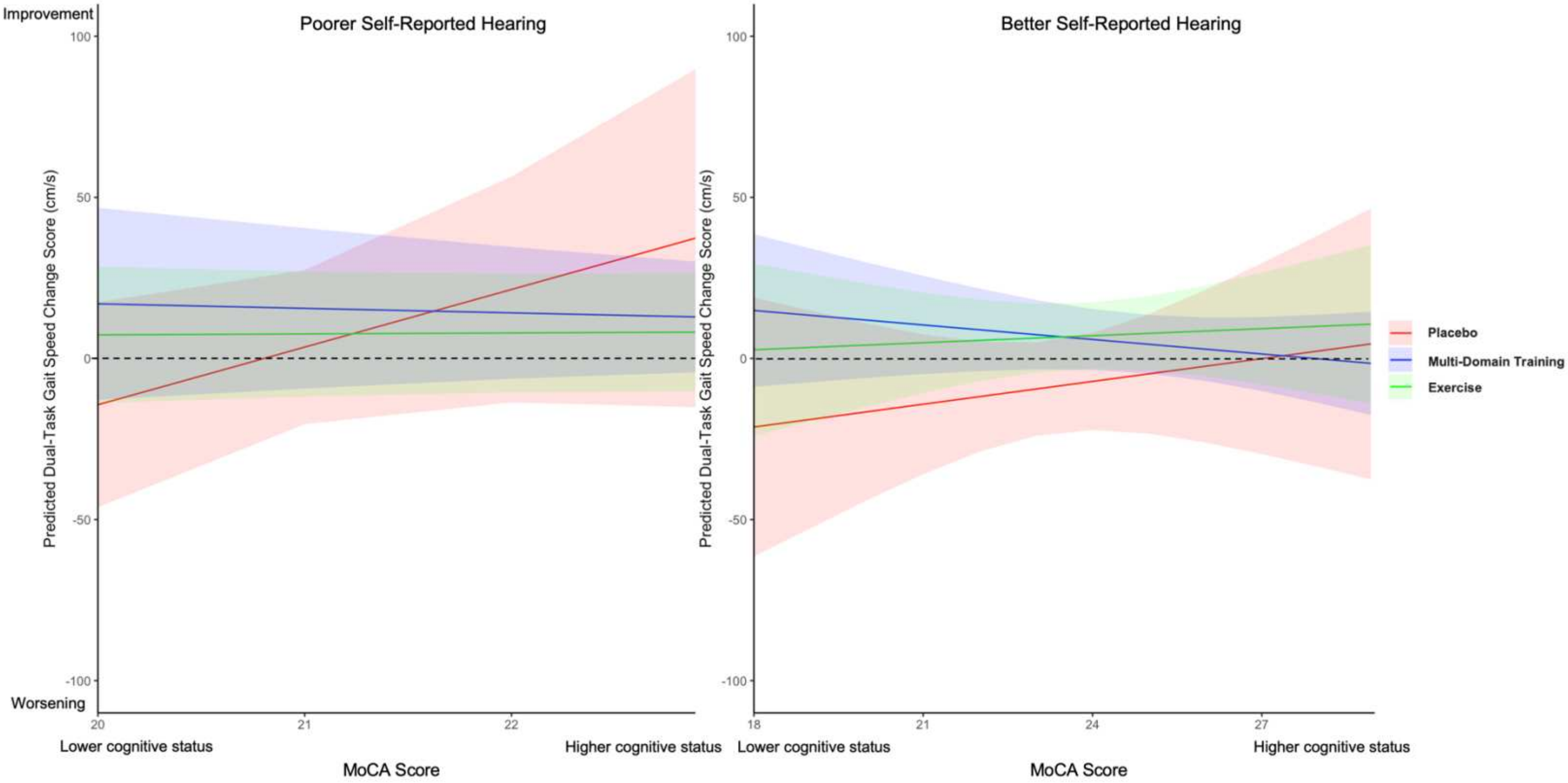
Effect of Hearing Ability on Dual-Task Gait Performance from Pre- to Post-Training: Interactions with Cognitive Status

Given the baseline findings demonstrating interactions between MoCA scores and our hearing measures on dual-task gait performance, we examined whether individuals with a greater severity of hearing loss and poorer cognitive functioning benefited differentially from the training compared to those with less severe impairments. We found significant HHIE-S by MoCA by Training interaction effects for dual-task gait speed, $F(2, 54) = 4.10$, $p = .021$, $\eta_p^2 = .13$ (Figure 3), stride time, $F(2, 53) = 4.98$, $p = .01$, $\eta_p^2 = .16$, and double-support time, $F(2, 51) = 5.72$, $p = .006$, $\eta_p^2 = .18$. Specifically, in participants with greater hearing complaints (i.e., higher HHIE-S scores), lower MoCA scores significantly predicted worsened dual-task gait speed ($\beta = 13.54$ cm/s, $SE = 5.47$, $p = .017$), stride time ($\beta = -70$ ms, $SE = 26.68$, $p = .01$) and double-support time ($\beta = -69.84$ ms, $SE = 26.21$, $p = .01$) following Placebo Training.

Additionally, we found significant CDTT by MoCA by Training interaction effects for dual-task gait speed, $F(2, 37) = 3.73$, $p = .033$, $\eta_p^2 = .17$ (Figure 4), stride time, $F(2, 34) = 3.98$, $p = .028$, $\eta_p^2 = .19$, and double-support time, $F(2, 36) = 5.92$, $p = .006$, $\eta_p^2 = .25$. Specifically, in participants with poorer CDTT performance (i.e., higher CDTT SRTs), lower MoCA scores significantly predicted improved dual-task gait speed ($\beta = -4.08$ cm/s, $SE = 1.37$, $p = .005$), stride time ($\beta = 32.45$ ms, $SE = 12.85$, $p = .016$) and double-support time ($\beta = 24.59$ ms, $SE = 7.40$, $p =.002$) following Multi-Domain Training. In contrast, in participants with poorer CDTT performance (i.e., higher CDTT SRTs), lower MoCA scores predicted worsened dual-task gait speed ($\beta = 23.23$ cm/s, $SE= 7.72$, $p = .005$), stride time ($\beta = -198.65$ ms, $SE = 70.5$, $p = .008$) and double-support time ($\beta = -110.05$ ms, $SE = 42.39$, $p = .014$) following Placebo training.

Figure 3

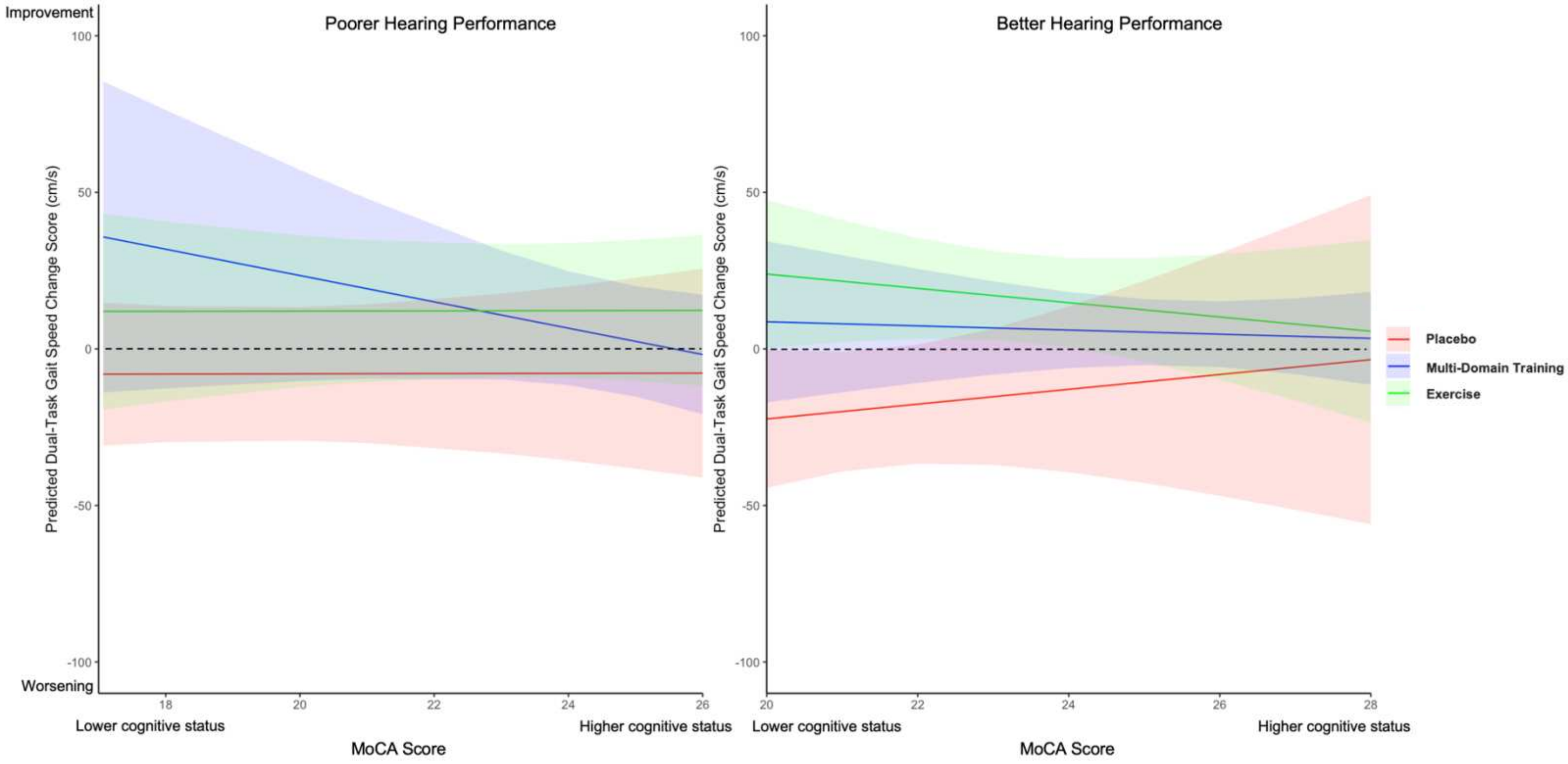
Linear Mixed Model of HHIE by Training by MoCA Interaction Effect for Dual-Task Gait Speed Change Scores from Pre- to Post-Training



Note. MoCA β estimates of dual-task gait speed change scores (ms) following Placebo Training (red), Multi-Domain Training (blue), and Exercise (green) across Poorer Self-Reported Hearing (left) and Better Self-Reported Hearing (right); Placebo Training consisted of balance and toning exercises with sham cognitive training; Multi-Domain Training consisted of aerobic-resistance exercise with cognitive training; Exercise consisted of aerobic-resistance exercise with sham cognitive training; Error bars correspond to the 95% confidence intervals of the estimates; MoCA = Montreal Cognitive Assessment; HHIE = Hearing Handicap Inventory for The Elderly - Screening Version; Better Self-Reported Hearing = HHIE-S scores less than 1SD below the mean; Poorer Self-Reported hearing = HHIE-S scores greater than 1SD above the mean; Dotted line represents point of inflection for improvement or worsening of dual-task gait speed following training (i.e., scores above zero indicate improvement and scores below zero indicate worsening). Dual-task performance was aggregated across the serial 1 subtractions, serial 7 subtractions, and semantic fluency conditions.

Figure 4

Linear Mixed Model of CDTT by Training by MoCA Interaction Effect for Dual-Task Gait Speed Change Scores from Pre- to Post-Training



Note. MoCA β estimates of dual-task gait speed change scores (ms) following Placebo Training (red), Multi-Domain Training (blue), and Exercise (green) across Poorer Hearing Performance (left) and Better Hearing Performance (right); Placebo Training consisted of balance and toning exercises with sham cognitive training; Multi-Domain Training consisted of aerobic-resistance exercise with cognitive training; Exercise consisted of aerobic-resistance with sham cognitive training; Error bars correspond to the 95% confidence intervals of the estimates; MoCA = Montreal Cognitive Assessment; CDTT SRT = Canadian Digit Triplet Test – Speech Response Threshold; Better Hearing Performance = SRTs less than 1SD below the mean; Poorer Hearing Performance = SRTs greater than 1SD above the mean; Dotted line represents point of inflection for improvement or worsening of dual-task gait speed following training (i.e., scores above zero indicate improvement and scores below zero indicate worsening). Dual-task performance was aggregated across the serial 1 subtractions, serial 7 subtractions, and semantic fluency conditions.

Effect of Hearing Ability on Dual-Task Gait Performance from Pre- to Post-Training: Sex-Specific Interactions

To examine whether the effect of hearing ability on dual-task outcomes following training differed across males and females, we stratified our analyses by sex. We found a significant HHIE-S by Time interaction effect in female participants for stride time, *F*(1, 140) = 5.39, $p = .021$, $\eta_p^2 = .04$, such that females with greater self-reported hearing complaints (i.e., higher HHIE-S scores), showed a significant reduction (i.e., improvement) in stride time, regardless of intervention arm ($\Delta = -42.45$ ms, *SE* = 13.0, $p = .001$). In contrast to this, analyses involving behavioural hearing performance in females revealed significant CDTT by Time by Training interaction effects in the opposite direction for double-support time, *F*(2, 101) = 8.48, $p < .001$, $\eta_p^2 = .14$, and stride time, *F*(2, 101) = 6.12, $p = .003$, $\eta_p^2 = .11$. Specifically, in female participants with better objective hearing performance (i.e., lower CDTT SRTs), stride time ($\Delta = -79.2$ ms, *SE* = 21.1, $p < .001$) and double-support time ($\Delta = -46.18$ ms, *SE* = 10.96, $p < .001$) significantly improved following Multi-Domain Training, though significantly worsened following Placebo Training (stride time: $\Delta = 116.8$ ms, *SE* = 31.5, $p < .001$; double-support time: $\Delta = 53.28$ ms, *SE* = 16.31, $p = .002$). We additionally found a significant CDTT by Time interaction effect in females for dual-task cognitive accuracy, *F*(1, 107) = 8.21, $p = .005$, $\eta_p^2 = .07$, such that accuracy scores significantly improved following training in participants with better objective hearing performance (i.e., lower CDTT SRTs), regardless of training modality ($\Delta = .19$ corr/s, *SE* = .09, $p = .036$).

In male participants, we did not find any significant effects of self-reported hearing loss on the degree of improvement in dual-task performance following training; however, we found significant effects for our behavioural hearing measure. Specifically, we found significant CDTT by Time by Training Group interaction effects for dual-task gait speed, *F*(2, 142) = 3.91, $p = .022$, $\eta_p^2 = .05$, and stride length, *F*(2, 140) = 7.77, $p < .001$, $\eta_p^2 = .10$, such that males with poorer objective hearing performance (i.e., higher CDTT SRTs) only showed significant improvements in gait speed (Δ = 9.51 cm/s, *SE* = 4.10, $p = .022$), and stride length (Δ = 8.09 cm, *SE* = 2.54, $p = .002$) following Multi-Domain Training.

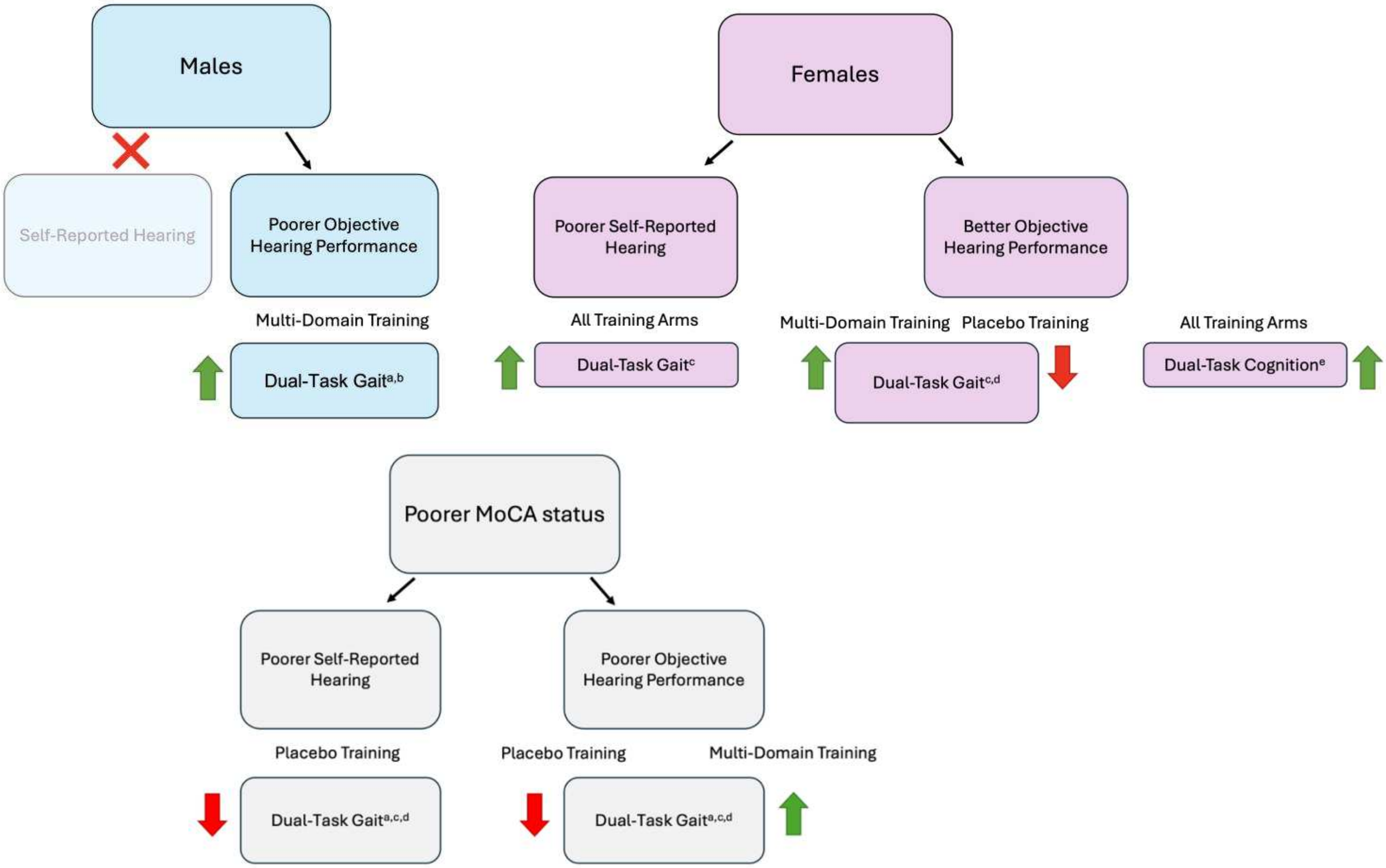
Discussion

By examining a subset of participants with MCI from the SYNERGIC trial who were co-enrolled in a longitudinal study that included a hearing evaluation, we aimed to examine whether hearing ability (including participants with clinical and subclinical hearing loss) affected dual-task performance at baseline and following 20-weeks of physical exercise training, alone or in combination with computerized cognitive training. Given the known sex differences in hearing loss and dementia, we further sought to examine whether any sex-specific interactions emerged with hearing ability on the degree of dual-task improvements following training.

Our baseline results demonstrated that MCI participants with a greater degree of hearing loss (measured by both self-report and behavioural testing) had poorer dual-task gait performance, including temporal aspects of gait (e.g., gait speed, stride time) as well as gait stability (e.g., stride length variability, double-support time). The relationship between hearing loss and dual-task performance at baseline appeared to be largely driven by the male participants. Regarding our training results, we found that dual-task gait significantly improved following multi-domain exercise and cognitive training in participants with a greater degree of self-reported hearing complaints, and in participants with poorer cognitive status combined with poorer objective hearing performance. We further found that training efficacy was moderated by interactions between sex and hearing ability, such that dual-task gait improved in males with poorer objective hearing and in females with better objective hearing following multi-domain training, as well as in females with greater self-reported hearing complaints (regardless of training arm). See Figure 5 for a schematic overview of the training results.

Figure 5

Schematic Overview of Training Results According to Sex and Cognitive Status Interactions



Note. The green upward arrows represent improved dual-task performance following training, whereas the red downward arrows represent a reduction in dual-task performance following training; [a]gait speed, [b]stride length, [c]stride time, [d]double-support time, [e]cognitive accuracy; Placebo Training consisted of balance and toning exercises with sham cognitive training; Multi-Domain Training consisted of aerobic-resistance exercise with cognitive training; MoCA = Montreal Cognitive Assessment; Objective hearing performance was measured using the Canadian Digit Triplet Test; Self-reported hearing was measured using the Hearing Handicap Inventory for The Elderly - Screening Version.

Effect of Hearing Ability on Dual-Task Performance at Baseline and Following Training

As anticipated, we found a greater magnitude of improvement in dual-task gait stability (i.e., stride time variability) following multi-domain physical exercise and cognitive training in participants with poorer self-reported hearing. Other research has shown similar synergistic effects on cognition and mobility in cognitively unimpaired older adults (Bherer et al., 2021) and older adults with MCI (Castellote-Caballero et al., 2024). Our results are novel in showing a synergistic effect of training on cognitive-motor dual-task outcomes in MCI participants with a greater degree of self-reported hearing loss. These findings are partially consistent with our previous training work in cognitively unimpaired older adults (Bruce et al., 2019b). Specifically, cognitively unimpaired older adults with hearing loss had similar levels of dual-task improvement following either a simultaneously or sequentially delivered physical exercise and cognitive training program, whereas older adults with normal hearing only improved following the sequential training format (Bruce et al., 2019b). Participants with hearing loss may have had greater opportunity for improvement due to greater dual-task costs observed at baseline under challenging listening conditions compared to normal hearing participants (Bruce et al., 2019a), allowing either approach to be beneficial.

Several mechanistic theories have been proposed to explain the association between hearing loss and reduced cognitive functioning (e.g., information degradation, sensory deprivation; Schneider & Pichora-Fuller, 2000), which may inform our training-related findings. For example, the sensory deprivation hypothesis suggests that over time, auditory deprivation may lead to temporal lobe atrophy and the re-allocation of attentional resources to compensate for an impoverished signal (Lin et al., 2014; Peelle & Wingfield, 2015; Powell et al., 2022). Dual-task interference may therefore be exacerbated in individuals with a higher degree of hearing loss due to alterations in brain structure that lead to changes in higher level brain function. Specifically, hearing loss may cause increased competition for cognitive control regions while dual tasking due to the re-allocation of attentional resources that occurs over time to support auditory processing (Powell et al., 2022). In the current study, we found that males with a higher degree of hearing loss (measured by both self-report and behavioural testing) had poorer dual-task gait and cognitive performance at baseline. These findings are consistent with a growing body of literature, which suggests that older adults with hearing loss have reduced dual-task gait and balance, as well as poorer working memory performance, compared to individuals with normal hearing (Wunderlich et al., 2024).

Given our baseline findings demonstrating poorer dual-task performance in participants with poorer hearing, our training results appear largely consistent with a compensation account of training (Lövdén et al., 2012). This theory posits that when intervention task demands exceed available resources, repeated training induces neural plasticity and promotes a higher level of change in performance following training. Our results are also consistent with compensatory scaffolding theories (Li et al., 2018; Reuter-Lorenz & Park, 2014), such that Multi-Domain Training may have increased the capacity for neural scaffolding in MCI participants with a greater degree of hearing loss, due to potential alterations in brain structure and function caused by changes in auditory processing over time.

Effect of Hearing Ability on Dual-Task Performance Following Training: Sex-Specific Interactions

Given potential sex differences in hearing loss and MCI, we further examined whether any sex-specific interactions emerged with hearing ability on the degree of dual-task improvements following training. When we stratified our analyses by biological sex, differential effects emerged depending on the hearing measure used and the sex of the participants. Specifically, we found a synergistic effect of Multi-Domain Training on dual-task performance in male participants with poorer objective hearing performance, as dual-task gait speed and stride length only significantly improved following physical exercise combined with cognitive training. While research has shown that hearing loss is more prevalent and more severe in males compared to females (Nolan, 2020), in the current study, we did not find any significant differences in hearing ability between sexes. Additionally, no other participant characteristics significantly differed between sexes, including age, years of education, global cognitive status, or hearing aid use. As such, it remains unclear what is driving these sex effects on dual-task performance before and after training.

One possible interpretation is that given that hearing loss tends to have an earlier age of onset in males compared to females, there may have been more time for structural and functional brain changes to occur, leading to increased competition for cognitive control regions while dual tasking. This is consistent with our baseline findings, which revealed that the association between hearing loss severity and dual-task performance was largely driven by the male participants. This idea echoes previous proposals of gradual age-related sensory and cognitive declines occurring in midlife followed by functional adaptations in the form of changes to attentional allocation and neural reorganization (Li & Lindenberger, 2002). Additionally, in a more recent longitudinal study by Boons et al. (2025), poorer peripheral hearing acuity was found to be associated with faster microstructural deterioration over time in a white matter tract involved in auditory processing. The link between hearing acuity and white matter integrity was stronger in low-frequency hearing thresholds, which tend to deteriorate at a faster rate in males compared to females (Dillard et al., 2024). Furthermore, using a similar sample as the current study, we have previously found sex differences in brain activation in relation to physical frailty (Bray et al., 2023b). Specifically, in male MCI participants, stronger functional brain connectivity between the right hippocampus and temporal gyrus positively correlated with increased frailty. While this previous study did not examine hearing loss specifically, it is possible that the male participants in our sample underwent greater structural and functional brain changes due to alterations in hearing capacity compared to females, leading to greater dual-task deficits at baseline and a greater opportunity for improvement following Multi-Domain Training. However, further research is needed to support this interpretation. Finally, gender-related factors such as occupation (e.g., fields with increased noise exposure) and lifestyle choices (e.g., smoking) may have differed across men and women in our sample and may have interacted with hearing capacity (Reavis et al., 2023). Nonetheless, *post hoc* analyses examining sex- and gender-based differences across other risk factors for dementia (e.g., hypertension, depression, smoking, diabetes) did not reveal any significant differences. Further research may therefore be warranted to better understand whether the sex-related interactions observed in the current study are due to biological sex differences or gender-related lifestyle factors.

In contrast to our findings in males, in female participants with better objective hearing performance, there was a synergistic effect of Multi-Domain Training on dual-task gait, and a positive impact of training on dual-task cognition, regardless of the training domain. However, female participants with greater subjective hearing complaints showed significant improvements in dual-task gait following training, regardless of the intervention arm. One potential reason for the disparity in our results across the self-reported and behavioural hearing measures may be that there was a weak association between hearing measures in our female participants. Indeed, we only found a significant correlation between HHIE-S and CDTT SRTs in male participants, such that a greater degree of self-reported hearing loss was associated with poorer CDTT performance. Further analyses categorizing hearing loss according to performance across each hearing measure (i.e., hearing loss was categorized as HHIE-S > 10; Ventry & Weinstein, 1983; CDTT SRTs > -10 dB SNR; Al-Yawer et al., 2023) demonstrated a significant difference across measures in females ($\chi^2 = 5.62$, $p = .018$), but not in males ($\chi^2 = .50$, $p = .481$). As such, it is possible that female participants endorsed an elevated level of hearing complaints amidst relatively preserved hearing capacity. Interestingly, other research in cognitively unimpaired older adults has found that males report greater perceived hearing difficulties compared to females, even after controlling for hearing loss and hearing thresholds (Hämäläinen et al., 2021; Humes, 2021). Our findings also echo what has been reported in the frailty literature. Specifically, while there is evidence of a male-female health survival paradox, such that females become frail earlier yet live longer than males (Gordon et al., 2017), research now suggests that this might be due in part to symptom over-reporting or poorer perception of self-rated health in females (Park & Ko, 2022).

Another interpretation of our results can be made by considering the baseline results, which demonstrated that in participants with better objective hearing performance, females had poorer dual-task cognitive accuracy compared to males. Consistent with the compensation account of training (Lövden et al., 2012), female participants may have had more opportunity for improvement following active training; however, they may have been at a greater disadvantage following the placebo training, due to the typical trajectory of cognitive, physical, and neural decline in MCI over time. This is consistent with a recent study which showed that in older adults with amnestic MCI, white matter fiber density declined at a faster rate following six months of sham cognitive training (i.e., completing crossword puzzles) compared to active cognitive training (i.e., memory and executive function training; Gozdas et al., 2024).

Effect of Hearing Ability on Dual-Task Performance Following Training: Interactions with Cognitive Status

Given the observed associations between hearing ability and dual-task performance, we wondered whether the severity of cognitive impairment would have an additional detrimental effect on dual tasking, and additionally, if the severity of cognitive impairment influenced training-related outcomes. Our results demonstrated that at baseline, in participants with poorer hearing, lower cognitive status (i.e., lower MoCA scores) predicted poorer dual-task gait performance (i.e., gait speed, stride time, stride length variability, double-support time, gait DTCs). We further found a synergistic effect of Multi-Domain Training in participants with poorer cognitive status combined with poorer objective hearing on temporal aspects of gait, as well as gait stability. Specifically, in participants with poorer objective hearing performance, poorer cognitive status predicted improvements in dual-task gait speed, stride time, and double-support time, only following physical exercise combined with cognitive training. Additionally, we found that following the Placebo Training, dual-task gait performance (i.e., gait speed, stride time, double-support time) declined in participants with poorer hearing and *lower* cognitive status, though improved in participants with poorer hearing and *higher* cognitive status.

These results are novel in that they provide insight into the types of training that promote the greatest magnitude of improvements depending on individual characteristics by considering hearing ability and cognitive functioning. According to the capacity theory, dual tasking leads to competition for limited resources, causing decrements in performance in one or both tasks (Salthouse et al., 1984; Woollacott & Shumway-Cook, 2002; Wright, 1981). As attentional resources may need to be re-allocated due to structural brain changes caused by alterations in auditory processing over time, dual-task effects are likely to be exacerbated in individuals with a greater degree of hearing loss. In addition to hearing loss, participants with lower cognitive status might have fewer cognitive resources to draw from while dual tasking, leading to an added detriment to dual-task performance. Indeed, research has shown that poor cognition mediates the relationship between sensory functioning and gait speed in older adults (Huang et al., 2019). This is consistent with our baseline findings, which demonstrated that participants with reduced cognitive and hearing functioning had poorer dual-task gait performance. These participants may have therefore had greater opportunity for improvement following physical exercise combined with cognitive training, consistent with a compensation account of training (Lövdén et al., 2012). These results are also consistent with our previous training work, where we demonstrated that in cognitively unimpaired older adults, participants with lower MoCA scores at baseline had a greater magnitude of improvement in dual-task working memory performance following training (Downey et al., 2022). Additionally, in the current study, participants with poor hearing and lower cognitive status appeared to be most disadvantaged following the Placebo Training. These results may suggest that participating in balance, stretching, and toning exercises, in addition to completing basic computer tasks does not prevent or slow the progression of cognitive and physical decline in this particularly at-risk group (i.e., low cognitive status, poor hearing).

We further found that in participants with poor hearing, higher cognitive status predicted a greater degree of dual-task gait improvements following the Placebo Training. Other research has shown that gross motor training, involving balance and stretching exercises, improves executive functioning (Berryman et al., 2014) and dual-task working memory performance (Downey et al., 2022) in cognitively unimpaired older adults. As such, it is plausible that a certain level of cognitive functioning is required to elicit benefits from the types of activities included in our Placebo Training. Additionally, research suggests that individuals with hearing loss may withdraw from social interactions due to increased listening effort, which makes conversing fatiguing (Pichora-Fuller et al., 2016). This may result in isolation and reduce physical activity, further contributing to cognitive and motor limitations due to hearing loss. For example, Mikkola et al. (2015) demonstrated that in cognitively unimpaired older adults, hearing loss was associated with reduced participation in group activities outside of the home. As all the interventions in the current study were in-person and comprised of small groups, those with hearing loss in the placebo treatment may have experienced an increase in their physical activity levels and number of social interactions, which may have contributed to improvements in dual-task gait. Notably, this may have only been observed in participants with poor hearing and *higher* cognitive status as these individuals might have been able to draw on additional cognitive resources to support dual-task gait performance. Future research into the effect of cognitive and physical training on dual-task outcomes using an at-home intervention protocol may be warranted, to better control for these factors (e.g., Downey et al., 2023).

Limitations

The results of this study should be considered in light of some limitations. While our overall sample size was satisfactory, our intervention groups were unequal in size, with fewer participants in the Placebo Training group. As such, careful consideration must be given when interpreting the results from the Placebo Training group, particularly when the training analyses were stratified by sex as there were fewer female participants compared to males. To preserve statistical power, we were also unable to stratify our analyses according to MCI subtype, which may further limit some of the interpretations and implications of our results (e.g., comparing amnestic vs. non-amnestic MCI). Additionally, our sample was comprised of normal hearing older adults, as well as individuals with clinical and subclinical hearing loss. The hearing measures included in the current study are continuous in nature, and while they allowed us to identify whether hearing ability predicted dual-task performance before and after training, it is important to highlight that poorer hearing may not be indicative of clinical hearing loss. For example, participants may have scored higher on the HHIE-S or had higher CDTT SRTs relative to our overall sample, though some participants might not have reached the clinical cut-off to be considered hearing impaired. However, evidence suggests that subclinical hearing loss can also impact cognitive functioning, consistent with our results (Golub et al., 2020). Additionally, supplementary analyses categorizing hearing loss according to an abbreviated pure-tone audiometry assessment revealed similar results as the current study (see Supplementary Material), further bolstering our interpretations made using the continuous hearing measures.

Furthermore, around sixteen percent of our sample wore hearing aids. As there is some evidence to suggest that improved signal quality (e.g., by hearing aid use) may benefit cognitive performance (e.g., Lin et al., 2023; Sanders er al., 2021), and cognitive dual-task performance (Soylemez et al., 2024) in older adults with hearing loss, our results may represent a more conservative estimate of participants' dual-task performance before and after training. Additionally, the behavioural hearing assessments were conducted without hearing aids, while the dual-task experiment was completed with hearing aids, which may have potentially interfered with the relationships observed. We note however that there was no record of the type of hearing aids worn or how long the hearing aids were used by the participants, so more detailed research examining the effect of hearing aid use on dual-task performance may be warranted.

Another potential limitation of the study design was that there was no active cognitive training paired with the balance and toning exercises. Due to this, it remains unclear whether the benefits observed in dual-task performance were specific to the multi-domain nature of the training, or whether improvements were driven by the cognitive training component. Using a balanced training design, where participants are allocated to four different combinations of interventions (i.e., active cognitive training vs. sham cognitive training; aerobic-resistance exercise vs. stretching and toning exercises), researchers have previously found mixed effects in cognitively unimpaired older adults. Specifically, Fraser et al. (2017) demonstrated a similar magnitude of improvement in cognitive-motor dual-task performance following any combination of active and control interventions, whereas Bherer et al. (2020) only found improvements in cognitive dual-task performance following cognitive training, or multi-domain cognitive training with physical exercise. Notably, there is significant heterogeneity across different multi-domain interventions, highlighting the need to consider individual difference factors, together with the type of intervention, in order to optimize training gains (Barha et al., 2022; Izquierdo et al., 2025). Further research with MCI individuals is needed to elucidate the effect of hearing ability on cognitive training efficacy more specifically.

Finally, our dual-task design was comprised of three different secondary cognitive tasks (i.e., serial 1 subtractions, serial 7 subtractions, semantic fluency), although our results were aggregated across these measures. Research suggests that low cognitive loads may improve gait and balance performance compared to single-task conditions in cognitively unimpaired younger and older adults, whereas motor dual-task costs increase at higher levels of cognitive task complexity (Huxhold et al., 2006; Li et al., 2012; Lövden et al., 2008). While aggregating across different levels of secondary cognitive task complexity may have impacted our results to some degree, Condition was included as a factor in our linear mixed effect models, and was either removed from the models if it did not significantly contribute to model fit, or did not interact with our other key factors (e.g., hearing ability, sex). Additionally, a study by Hunter et al., (2018) demonstrated that low levels of cognitive task complexity (i.e., Serial 1 subtractions) negatively impacted gait velocity compared to single-task gait in MCI participants, but not in cognitively unimpaired older adults. As such, the point of inflection, wherein the cognitive task begins to interfere with mobility performance, appears to occur at lower levels of cognitive task complexity in cognitively impaired older adults, which bolsters our decision of aggregating the results across the three secondary cognitive tasks.

Conclusions

The current study provides novel insights into the types of training that promote the greatest magnitude of improvements in cognitive-motor dual-task performance in older adults with MCI, by considering interactions between hearing ability, biological sex, and cognitive functioning. Overall, our results suggest that there is a potentially synergistic effect of physical exercise combined with cognitive training in older adults with MCI who have a greater degree of hearing loss. This effect appears to be strongest in males, as well as in individuals with poorer hearing combined with lower cognitive status. Our training results in females varied according to the hearing measure used, which may be explained by the poorer concordance across the self-report and behavioural hearing measures in females than in males, with some females endorsing an elevated level of self-reported hearing difficulty despite relatively preserved performance on the CDDT hearing test.

The detriment to dual-task performance may be exacerbated in MCI individuals with the additional challenge of hearing loss due to associated neural alterations and cortical reorganization. This challenge appeared to be reduced by Multi-Domain physical exercise and cognitive training, whereby increasing physical and higher-level cognitive resources may have enhanced compensatory scaffolding. Older adults with MCI are at a greater risk for falls compared to cognitively healthy older adults and, conversely, slow gait speed predicts cognitive decline (Montero-Odasso et al., 2012b). As such, preserving dual-task gait and cognitive performance through physical exercise in combination with cognitive training may be critical for mitigating further cognitive and physical decline during this early prodromal stage, particularly in individuals with hearing loss.

CHAPTER FIVE:

GENERAL DISCUSSION

The central goal of this dissertation was to elucidate the processes and factors that underlie and influence changes in cognitive-motor dual-task performance following cognitive and physical interventions in older adults. Specifically, two main questions were addressed throughout this dissertation: 1) what processes or mechanisms underlie improvements in cognitive-motor dual tasking in older adults following training, including physiological, cognitive, and neural adaptations; and 2) what individual difference factors (such as age, hearing ability, cognitive functioning) influence training efficacy on cognitive-motor dual-task outcomes? In the following text, I summarize the main objectives and results of each study, provide a narrative on the aforementioned themes by synthesizing the results across the three studies, and discuss the theoretical and clinical implications of this research.

Summary of Presented Studies

In Study 1 (i.e., Downey et al., 2022), we investigated the cognitive and physiological mechanisms underlying changes in cognitive-motor dual-task performance following either executive function training, aerobic exercise, or gross motor coordination training in cognitively unimpaired older adults. Overall, we found significant improvements in cognitive DTCs following training, with a similar magnitude of improvement observed across training arms. Regarding potential mechanisms of action, we found independent improvements in set-shifting and inhibitory control following EF training and energy cost of walking following gross motor coordination training. Cardiorespiratory fitness did not significantly improve following aerobic exercise. Regarding individual difference factors, we found that lower baseline cognitive functioning was associated with greater improvements in cognitive DTCs.

To better understand the neuroplastic changes that may accompany or underlie improvements in cognitive-motor dual-task performance following training and how this might be moderated by age, in Study 2, we investigated the relationship between neural activity and dual-task performance following executive function training in middle-aged and older adults. We generally found that increased brain activity from single-task to dual-task predicted lower dual-task costs following executive function training, consistent with a neural compensation perspective. Additionally, participants who demonstrated a greater magnitude of improvement on near-transfer tasks tended to show a pattern of neural compensation. Regarding individual difference factors, we found that cognitive and gait DTCs significantly improved following executive function training, with differential effects depending on age and baseline cognitive status. Specifically, a larger magnitude of improvement in cognitive DTCs was observed following training in participants with higher baseline cognitive functioning, whereas for gait DTCs, a greater magnitude of improvement was observed in middle-aged adults with higher cognitive status, and in older adults with lower cognitive functioning. Furthermore, we found differential patterns of brain activity during dual tasking following training according to age and cognitive status (described in greater detail within the theme of individual differences).

Study 3 was motivated by the findings from Studies 1 and 2, which revealed an effect of baseline cognitive functioning on training efficacy in older adults, such that we wondered about the potential impact of cognitive performance on dual-task outcomes following training in a sample of older adults who already presented with cognitive difficulties (i.e., MCI). Additionally, given the intersection between auditory, cognitive, and motor functioning in late adulthood, we were interested in exploring the impact of hearing ability on cognitive-motor dual-task performance following exercise, alone or in combination with EF training. Finally, given the known sex differences in hearing loss and dementia, we explored whether there were any interactions between sex and hearing ability on the magnitude of training gains. Overall, we found that dual-task gait significantly improved following multi-domain exercise and cognitive training in participants with a greater degree of self-reported hearing complaints. Regarding sex differences, we found greater improvements in dual-task gait in males with poorer objective hearing and in females with better objective hearing following multi-domain training, as well as in females with greater self-reported hearing complaints (regardless of training arm). In participants with poorer hearing, lower baseline cognitive functioning predicted greater levels of dual-task gait improvement following exercise and cognitive training, and a decline following placebo control training.

Training Mechanisms

The interventions across our three studies were comprised of the following: executive function training (targeting divided attention, working memory and updating, inhibitory control), aerobic exercise (recumbent and upright cycling, walking), gross motor abilities training (targeting coordination, agility, balance), upper and lower body resistance training, and active control arms (e.g., stretching, balance, and toning exercises; video watching and internet searches). The potential physiological, cognitive, and neural processes underlying or accompanying dual-task improvements following these different cognitive and physical training interventions are described below.

Mechanisms underlying physical training interventions. Consistent with our hypothesis, in Study 1, we demonstrated that the energy cost of walking reduced following training, with a large effect size found following gross motor coordination training specifically. Although not reported in the manuscript, supplementary correlational analyses revealed that in the gross motor coordination training group, improvements in the energy cost of walking positively correlated with improvements in cognitive DTCs (*r* = .598, *p* = .040), providing a more direct link between training-related metabolic expenditure changes and dual-task improvements. Indeed, increasing coordinated walking abilities, thereby reducing the energy cost of walking, may have reduced the physical and cognitive demands of the walking task (Van Swearingen & Studenski, 2014), enhancing the availability of resources to be allocated to the cognitive domain while dual tasking.

These findings are consistent with research demonstrating improved executive functioning and processing speed following gross motor coordination training (Berryman et al., 2014; Forte et al., 2013; Voelcker-Rehage et al., 2011). Interestingly, Voelcker-Rehage et al. (2011) found parallel evidence of decreased prefrontal brain activation following gross motor training, which was interpreted to suggest more efficient neural processing. This appears to conflict with our results from Study 2, which found evidence of neural compensation following executive function training (i.e., increased prefrontal brain activation from single-task to dual-task correlated with improvements in gait DTCs). Differences across training modalities (i.e., cognitive vs. physical) and outcome measures (i.e., single-task cognition vs. cognitive-motor dual-task performance) may explain such inconsistencies. Future research directly examining the neural changes underlying cognitive-motor dual-task improvements following gross motor coordination training may elucidate the potential neural contributions that may accompany increased motor efficiency.

Regarding aerobic exercise, in Study 1, cardiorespiratory fitness did not significantly improve following training (small effect). Additionally, supplementary correlational analyses did not reveal any significant associations between the level of improvement in cardiorespiratory fitness (i.e., VO_{2peak}) and cognitive DTCs following aerobic exercise ($r = .118$, $p = .729$). These findings are partly inconsistent with previous research. For example, Bherer et al. (2021) found that in older adults (aged 70-79 years old), improvements in processing speed were mediated by increased cardiorespiratory fitness following 12 weeks of multicomponent physical exercise training (i.e., aerobic exercise, resistance training). In contrast, in younger old participants (< 70 years old), increased aerobic capacity did not mediate improvements in task set costs (i.e., ability to maintain different response alternatives in working memory). Given that the average age of participants in the aerobic exercise group in Study 1 was 68.2 years, it is possible that increased cardiorespiratory fitness following aerobic exercise may not mediate cognitive functioning until later in life, when age-related physical, cognitive, and neural changes are more prominent. Indeed, in Study 1, we found that the aerobic exercise group had relatively high baseline cardiorespiratory fitness, potentially limiting the opportunity for improvement following training.

Previous research has further demonstrated significant associations between cardiorespiratory fitness, structural and functional brain changes, and cognitive performance. For example, Oberlin et al. (2016) found that in older adults, increased white matter integrity across several white matter tracts mediated the relationship between aerobic capacity and spatial working performance. Additionally, Wong et al. (2015), demonstrated that increased activity in the anterior cingulate cortex and supplementary motor area mediated the relationship between cardiorespiratory fitness and cognitive dual-task performance. While these studies did not directly examine the effect of aerobic exercise on cardiorespiratory fitness, they provide evidence for the role of structural and functional brain changes that may co-occur in the context of higher cardiorespiratory fitness. It is possible that we did not find a direct association between change in cardiorespiratory fitness and improvements in cognitive DTCs following aerobic exercise in Study 1 due to the relatively short duration of the training (i.e., 12 weeks), which contrasts with the aforementioned studies which were cross-sectional in nature and likely reflect consistent physical activity levels over a longer time period. Overall, in a systematic review by Angevaren et al. (2008), the authors concluded that there was insufficient evidence that improvements in cognitive function following aerobic exercise were due to improvements in cardiovascular fitness, consistent with our results.

Other mechanisms aside from cardiorespiratory fitness may therefore be implicated in the positive effects of aerobic exercise on cognitive-motor dual-task performance, as was observed in Studies 1 and 3. While aerobic exercise has been shown to improve several aspects of executive functioning in older adults (see Ye et al., 2024 for review), we did not find evidence of improved cognitive flexibility or inhibitory control following aerobic exercise in Study 1. Supplementary correlational analyses also did not reveal any significant associations between changes in Stroop switching (r = -.490, p = .126) or inhibition (r = -.369, p = .264) and the magnitude of improvement in cognitive DTCs following aerobic exercise. However, in examining divided attention using a visual discrimination task (i.e., reaction times on dual-mixed trials), the correlation approached significance (r = .506, p = .082), suggesting that improvements in divided attention following aerobic exercise may mediate improvements in cognitive DTCs. This is consistent with several studies demonstrating improvements in dual-task processing in older adults following aerobic exercise (e.g., Hawkins et al., 1992; Kramer et al., 2002).

Taken together, the potential mechanisms underlying cognitive-motor dual-task improvements following physical training interventions are complex and likely overlap. The results from the studies included in this dissertation provide compelling evidence for an association between reduced metabolic energy expenditure and improved cognitive DTCs following coordination training. The mechanisms underlying aerobic exercise-induced improvements in cognitive-motor dual-task performance are less clear, and may involve a combination of processes, including increased aerobic capacity, improved task-switching abilities, and structural brain changes. Finally, while Study 3 involved multicomponent physical exercise comprised of aerobic exercise and resistance training, we did not directly examine the mechanisms underlying dual-task improvements following resistance training, and thus future research into this training modality may be warranted.

Mechanisms underlying cognitive training. As previously described, gait performance has been found to correlate with executive functioning and prefrontal cortex activity (Demnitz et al., 2016; Hamacher et al., 2015), making executive functions a candidate mechanism to target in the context of intervention. Indeed, from a neural overlap perspective, the greatest potential for transfer occurs when the trained task and outcome measure functionally overlap and engage similar neural circuitry (Lustig et al., 2009). In line with this, our results from Study 1 demonstrated significant improvements in cognitive DTCs, as well as inhibitory control and task-switching abilities, following executive function training. Interestingly, in supplementary correlational analyses, we did not find any significant associations between the magnitude of improvements on the executive function tasks and cognitive DTCs (i.e., inhibition: $r = .413$, $p = .269$; Stroop switching: $r = .286$, $p = .456$; dual-mixed: $r = .142$, $p = .762$).

These findings partially conflict with results reported by Li et al. (2010), who found significant correlations between the level of improvement in dual-task single support balance and the level of improvement on the trained executive function tasks, with stronger correlations found for the trained tasks requiring increased divided attention demands. Of note, the executive function tasks included in Study 1 were comprised of near-transfer tasks (i.e., a variant of the trained task with different stimuli), which may explain such inconsistencies across studies. It is therefore possible that improvements in inhibitory control and task switching abilities mediated improvements in cognitive-motor dual-task performance, though our measures may not have been sensitive enough to capture this.

In addition to executive function performance, neuroplastic changes can also be examined following executive function training to better understand the putative neural mechanisms that may accompany or underlie cognitive-motor dual-task improvements. The results from Study 2 demonstrated significant associations between the change in cognitive and gait DTCs and prefrontal cortex activity following executive function training. Specifically, a greater increase in brain activity (from single-task to dual-task) following training predicted a greater improvement in cognitive and gait DTCs following executive function training, particularly in participants who showed a greater magnitude of improvement on near-transfer divided attention tasks.

The results from Study 2 broadly align with a neural compensation perspective, given that increased recruitment of prefrontal brain regions appeared to support cognitive-motor dual-task performance following training. According to the revised Scaffolding Theory of Aging and Cognition, Reuter-Lorenz and Park (2014), posit that training may induce scaffolding, or the recruitment of additional neural networks, during learning or task acquisition. However, it is also speculated that over time, training may increase neural efficiency of the primary brain structures and networks, which would reduce the need for neural scaffolding to occur (Reuter-Lorenz & Park, 2014). Indeed, there is some evidence that executive function training can reduce the loss of, or even increase, grey matter volume in older adults (Nguyen et al., 2019b). Given that neural scaffolding is thought to be stimulated in the face of age-related structural brain decline (Park &

Reuter-Lorenz, 2009), if improvements in brain structure are observed following training, it may reduce the reliance on neural scaffolding to support goal achievement. Given that the duration of our training protocol was relatively brief (i.e., 12 weeks), it is possible that the observed compensatory response may reflect a temporary neural adaptation, before executive control processes are better consolidated.

Our results examining whether the magnitude of improvement on the computerized executive function near-transfer tasks influenced the relationship between neural activity and dual-task performance following training lend some support for this interpretation. Specifically, we tended to see a pattern of neural compensation at baseline, particularly in older participants. Following training, in participants who showed a greater degree of improvement in divided attention performance, the pattern of neural compensation reduced, though remained significant, perhaps suggesting reduced reliance on neural scaffolding to support dual-task performance. This is consistent with a systematic review on the effects of executive function training on cognitive and neural outcomes in older adults, such that, across studies, there was a general pattern of increased subcortical and decreased frontal and parietal activation, possibly indicating reduced reliance on compensatory neural mechanisms (Nguyen et al., 2019b).

The studies discussed thus far have largely investigated the effects of computerized cognitive training on brain activity in the context of single-task cognitive performance. Only one study to our knowledge has examined the relationship between cognitive training-related improvements in dual-task gait and neural activity. Specifically, Marusic et al. (2022) measured brain activity in older adults using EEG during an offline sensorimotor task and found a correlation between reduced P2 latency (i.e., lower visual-evoked potential latency) and faster gait speed following cognitive training. These results were interpreted to reflect a more efficient recruitment of neuronal resources induced by training (Marusic et al., 2022). Differences across study methodologies may explain such inconsistencies with our findings, including how brain activity was measured (i.e., fNIRS vs. EEG) and when brain activity was captured (i.e., during dual tasking versus an offline sensorimotor task). Despite these differences, the results from our study and Marusic et al., (2022) underscore the importance of cognitive training interventions to target common brain substrates involved in cognition and mobility (i.e., frontal cortex) to improve cognitive-motor dual-task performance.

Taken together, the studies in this dissertation contribute novel insights to the literature by elucidating the potential mechanisms underlying cognitive-motor dual-task improvements following computerized cognitive training. Specifically, we found evidence of compensatory neural scaffolding following targeted executive function training, which appeared to accompany or underlie improvements in inhibitory control, task-switching abilities, and cognitive-motor dual-task performance. Of note, the neural scaffolding observed may be a temporary neuroplastic change that preludes increased consolidation of executive function processes or structural brain changes elicited by prolonged divided attention training. As the relationship between brain activity and dual-task performance was stronger in participants who demonstrated greater benefit on near-transfer divided attention tasks, our results suggest that the observed cognitive-motor dual-task improvements are likely due to an increase in task switching processes specifically, rather than other cognitive processes inherent to the training (e.g., processing speed, visual-spatial processing, etc.).

Effect of Individual Difference Factors on Training Efficacy

A second central theme of this dissertation and an emerging focus in the cognitive-motor dual-task literature is that of individual differences. Specifically, a growing body of research has investigated how individual difference factors, such as age, and cognitive and physical capacity, impact dual-task performance (e.g., Holtzer et al., 2005; Wollesen & Voelcker-Rehage, 2019; Wollesen et al., 2016; Wollesen et al., 2017). A novel contribution of the current dissertation is in investigating how inter-individual differences impact the *efficacy of interventions* in improving cognitive-motor dual-task performance. Several individual difference factors were examined throughout this dissertation, including age, baseline level of cognitive functioning, hearing ability, and sex. The following sections synthesize the results across the three studies using an individual differences perspective by addressing questions concerning compensation versus magnification, task prioritization, and neural adaptations.

Compensation versus magnification. As previously described, Lövden et al. (2012) proposed two opposing views – magnification and compensation - to conceptualize how baseline cognitive functioning might influence one's potential to benefit from training. The magnification perspective suggests that individuals with higher cognitive capacity should improve more from training due to a higher propensity to acquire, implement, and refine effortful cognitive strategies. In contrast, the compensation perspective suggests that individuals with lower cognitive capacity or who utilize inefficient cognitive strategies will have greater opportunity for improvement from cognitive training (Lövden et al., 2012).

Across the three studies included in this dissertation, we found mixed evidence for training-related compensation or magnification. In using baseline MoCA performance as a proxy for one's capacity to benefit from training, we found that compared to older adults with higher baseline cognitive functioning, older adults with lower cognitive status showed a greater magnitude of improvement in cognitive DTCs following cognitive or physical training (Study 1) and gait DTCs following EF training (Study 2). These findings align more with a compensation perspective and are consistent with research demonstrating a greater magnitude of improvement in cognitive performance in older adults with lower baseline cognitive capacity following working memory and executive function training (Hering et al., 2017; Shaw & Hosseini, 2021).

Our results extend these findings by demonstrating evidence of compensation in cognitive-motor dual-task performance following training. It appears that increasing cognitive resources through EF training allowed older adults to adopt a postural prioritization strategy (Li et al., 2001), such that gait performance became facilitated by the addition of a cognitive load following training (Study 2). Given that poorer executive functioning in older adults is associated with reduced gait speed, increased gait variability, and increased risk for falls (Demnitz et al., 2016), these individuals may have used the increased cognitive resources acquired from training to maintain gait performance while dual tasking. However, these findings appear to conflict with those in Study 1, as cognitive DTCs became facilitated following exercise or cognitive training in older adults with lower baseline cognitive functioning. Given that two out of the three interventions in Study 1 were comprised of physical exercise, it is possible that increasing physical resources through training could have improved physical self-efficacy, leading to a greater allocation of attentional resources to the cognitive domain while dual tasking. Indeed, research has shown that increased falls efficacy in older adults correlates with better balance performance (Kressig et al., 2001; Myers et al., 1996) and reduced gait DTCs (Wollesen & Voelcker-Rehage, 2019), and that exercise may reduce fear of falling (see Kendrick et al., 2014 for review).

We also found evidence of magnification when using baseline MoCA performance as a proxy of training efficacy. Specifically, we found that following EF training, cognitive DTCs only significantly improved in middle-aged and older adults with higher baseline cognitive status, and that gait DTCs only improved in middle-aged adults with higher baseline cognitive functioning (Study 2). These results echo previous findings from the mnemonic training literature, such that positive correlations have been observed between baseline cognitive abilities and the magnitude of improvements in memory performance (Kliegl et al., 1990; Verhaegen & Marcoen, 1996).

Our results extend these findings by providing evidence of magnification in middle-aged adults, following executive function training, and in cognitive-motor dual-task performance. It appears that the middle-aged adults with high cognitive capacity were able to acquire and improve executive control processes, allowing them to equally allocate attentional resources across both cognitive and motor domains while dual tasking. In contrast, older adults with higher baseline cognitive functioning appeared to allocate more resources to the cognitive domain, as these participants also showed an increase in gait DTCs following training. In examining baseline performance, it appeared that the older adults with higher cognitive functioning prioritized gait performance, as demonstrated by the relatively little gait DTCs and elevated cognitive DTCs, consistent with a postural prioritization strategy (Li et al., 2001). It is possible that increasing cognitive resources through EF training led to a shift in postural prioritization, with increased allocation of attentional resources to the cognitive domain, while maintaining gait performance.

Hearing loss also appears to be a relevant individual difference factor to estimate one's capacity to benefit from training. Consistent with the compensation perspective, in Study 3, we found that MCI participants with greater hearing complaints showed a greater magnitude of improvement in dual-task gait following multi-domain exercise and cognitive training compared to participants with better self-reported hearing. Additionally, we found that when lower hearing ability was compounded with poorer baseline cognitive functioning, participants showed a greater magnitude of improvement in dual-task gait following multi-domain training. Our baseline results lend further support for the compensation perspective, given that participants with poorer hearing and lower cognitive functioning had reduced dual-task performance, suggesting a greater opportunity for improvement following training.

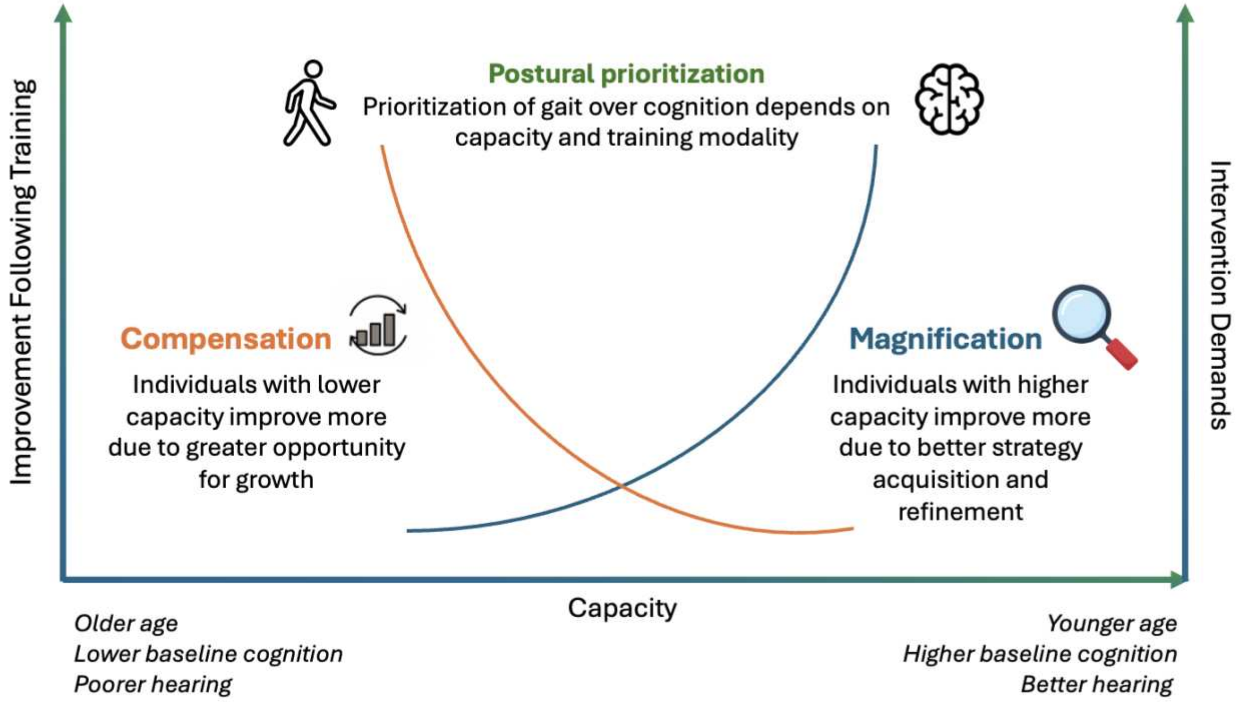
These results extend our previous findings in cognitively unimpaired older adults (Bruce et al., 2019b), where we showed that dual-task performance improved to a similar magnitude following simultaneously or sequentially delivered physical exercise and cognitive training in older adults with hearing loss. This was in contrast to older adults with normal hearing who only improved following the sequential training format, suggesting that participants with hearing loss may have had greater opportunity for improvement, allowing either approach to be beneficial (Bruce et al., 2019b). Additionally, our results are consistent with findings from Lin et al. (2022), who demonstrated that a hearing aid intervention led to significantly reduced cognitive decline over a three-year period, but only in a subset of participants who were older, had more risk factors for cognitive decline, and had lower baseline cognitive performance.

Finally, we found differential accounts of compensation and magnification when hearing ability was stratified by biological sex. Specifically, in Study 3, we found evidence of compensation in male MCI participants with poorer central hearing and in female MCI participants with poorer subjective hearing, who showed greater improvements in dual-task gait following training, compared to those with better hearing. As previously described, the compensation perspective suggests that when intervention task demands exceed available resources, repeated training induces neural plasticity and promotes a greater magnitude of improvement in performance after training (Lövden et al., 2012). Given that hearing loss tends to present earlier in males than females (Pearson et al., 1995), male participants may have had fewer available resources or greater competition amongst resources, allowing for a greater disparity between the intervention and task demands, thereby promoting dual-task improvements following training. This is consistent with our baseline results, which showed that the association between hearing ability and dual-task performance was largely driven by the male participants. In contrast, we found evidence of magnification in female MCI participants with better objective hearing, who had greater improvements in dual-task gait and cognition following training compared to those with poorer objective hearing. Given that the interventions were conducted in a group format (with a high probability of background noise), it is possible that better hearing ability allowed for increased comprehension and integration of the task instructions, which may have led to far transfer effects on dual-task performance. Indeed, we have previously shown that under noisy conditions, older adults with normal hearing have lower cognitive DTCs compared to older adults with hearing loss (Bruce et al., 2019a).

In summary, the behavioural results from the three studies included in this dissertation lend differential support for a compensation or magnification perspective, depending on the individual difference factor (cognition, age, hearing ability, sex), the domain being measured (cognitive vs. gait), and the modality of the intervention (cognitive vs. physical; Figure 1). Indeed, we found potential evidence for a shift in postural prioritization according to the baseline level of resources available to the individual, as well as which resources were strengthened following training. Similar to the framework proposed by Lövden et al. (2012), but taking a slightly more nuanced perspective, our results highlight the importance of considering the level of resources available to the individual, the demands imposed by the intervention, as well as the *amount of competition amongst resources* (i.e., in the context of hearing loss, during cognitive-motor dual tasking) when determining the capacity for improvement following training.

Figure 1

Magnification Versus Compensation Effect on Dual-Task Performance Following Training



Neural adaptations following training. In addition to our behavioural outcomes, individual difference factors also appeared to influence neural activity during dual tasking following training. Regarding cognitive dual-task performance, in Study 2, we found that older adults with lower baseline cognitive functioning moved from a pattern of neural compensation to increased neural efficiency following EF training. These findings are partially inconsistent with previous literature. Specifically, studies have shown evidence of neural inefficiency during dual tasking in individuals with fewer resources, such as in older adults with PD (Maidan et al., 2016), lower frontal brain volume (Ross et al., 2021), and lower cognitive functioning (i.e., Holtzer et al., 2020). Additionally, evidence of neural compensation has been found following cognitive or physical training interventions in older adults with MCI and AD (i.e., higher brain activity associated with improvements in mobility; Kyo et al., 2022; Parvin et al., 2020).

As previously described, compensatory theories of cognitive aging posit that neural scaffolding, or the upregulation of brain activity, operates to counteract the adverse effects of age-related neural and functional decline (Park & Reuter-Lorenz, 2009; Reuter-Lorenz & Park, 2014). Given that our participants in Study 2 were considered cognitively healthy (i.e., neuropsychological test performance fell within the age-normative range), it is possible that the older adults with lower global cognitive functioning remained capable of recruiting prefrontal regions to support divided attention at baseline. Following EF training, the walking task may have become less executively demanding, which may have reduced the need for compensatory scaffolding in frontal brain regions during cognitive-motor dual tasking, allowing for increased neural efficiency. This is consistent with research demonstrating decreased neocortical activity, with task-specific activity increases in other brain regions, following adaptive working memory training (Brehmer et al., 2011; 2012) and motor learning (Nyberg et al., 2006).

Also contrary to our initial expectations, in Study 2, older adults with higher baseline cognitive functioning were found to show a pattern of neural inefficiency at baseline, which shifted to a pattern of neural compensation following EF training. Instead, we expected to observe either a pattern of neural efficiency or neural compensation at baseline, with increased neural efficiency following EF training. This hypothesis was based upon findings of reduced PFC activity from single- to dual-task walking in older adults with higher levels of cognitive reserve (Holtzer et al., 2022), as well as research demonstrating an association between increased brain activity from single- to dual-task and lower gait speed dual-task costs in healthy older adults (Maidan et al., 2016). Nevertheless, evidence of neural inefficiency has also been observed in cognitively normal older adults (Stojan et al., 2023). In examining our baseline behavioural data, the older adults with higher baseline cognitive functioning appeared to prioritize gait performance while dual tasking (i.e., had greater costs in the cognitive domain). As such, it is possible that the neural inefficiency that was observed reflects the prioritization of the motor task. In contrast, following EF training, older adults with higher baseline cognitive capacity demonstrated a significant decline in cognitive DTCs, though an increase in gait DTCs, which, as previously described, may reflect a shift in postural prioritization strategy. From a neural perspective, this shift of attentional allocation to the cognitive task may have increased the associated task demands, leading to increased frontal recruitment to support performance.

In addition to baseline cognitive capacity, hearing ability may also impact neural adaptations following training. We conducted exploratory analyses following Study 2, which revealed that in participants with poorer hearing (i.e., PTA ≥ 35 db HL), a greater increase in HbO levels from single-task to dual-task predicted lower cognitive DTCs at baseline, suggestive of neural compensation. Following EF training, in participants with poorer hearing, higher PFC activity marginally predicted lower gait DTCs, also consistent with neural compensation. According to the sensory deprivation hypothesis, prolonged auditory underload can lead to morphological and functional brain changes, such as temporal lobe atrophy and the re-allocation of attentional resources to compensate for a reduced auditory signal (Lindenberger & Baltes, 1994; Powell et al., 2022). In older adults with hearing loss, these changes may stimulate compensatory scaffolding when performing tasks requiring higher level cognitive control. While this is largely consistent with our findings using peripheral hearing acuity, our participants were comprised of experienced hearing aid users, and so peripheral hearing should be partially corrected. Nevertheless, in a study by de Boer et al. (2022), the authors found that hearing aid use did not moderate the relationship between hearing loss and brain structure, suggesting that morphological brain changes due to hearing loss may not be reversed with the correction of peripheral hearing.

Furthermore, effortful listening theories posit that hearing loss increases the cognitive complexity and demands associated with listening, leading to the recruitment or reallocation of attentional resources to comprehend an impoverished auditory signal (Lindenberger & Baltes, 1994; Pichora-Fuller, 2003; Schneider & Pichora-Fuller, 2000). This theoretical model also appears to align with our findings of neural compensation in older adults with poorer hearing acuity, although it raises the question of how hearing aid use may impact neural adaptations. While hearing aid use has been speculated to reduce listening effort (e.g., Downs, 1982), results from a more recent systematic review did not find any scientific evidence to indicate that hearing aid amplification decreases listening effort (Ohlenforst et al., 2017). As such, it is possible that the auditory signal remains impoverished to some degree in hearing aid users, thereby increasing listening effort, which could have upstream effects on functional neural reorganization and compensatory scaffolding.

Following EF training, in Study 2, we found some evidence to suggest increased neural compensation for dual-task gait in participants with poorer hearing acuity. These results are consistent with findings from Study 3, which demonstrated significant improvements in dual-task gait following multi-domain training in MCI participants with a greater degree of self-reported hearing complaints. Across both studies, it appears that training preferentially benefited gait over cognitive dual-task performance in participants with poorer hearing, consistent with previous research demonstrating that older adults with hearing loss tend to adopt a postural prioritization strategy (Bruce et al., 2019a; Lau et al., 2016). Our findings could therefore suggest that training induced an increased reliance on prefrontal brain regions to support gait performance in individuals with poorer hearing. Nevertheless, given the small sample size included in our exploratory analyses, further research is needed to better support this interpretation.

Taken together, the results across the studies included in this dissertation highlight the importance of considering how inter-individual differences, such as age, cognitive functioning, and hearing ability, not only impact behaviour, but also brain function before and after training. Investigating how neural activity adapts following training using an individual differences approach may elucidate the mechanisms that lead some older adults to demonstrate transfer effects over others. While this area of research is growing, there is limited research investigating how inter-individual differences impact training efficacy on cognitive-motor dual-task performance, making our results novel and relevant.

Limitations and Future Directions

There are many strengths to the studies included in this dissertation, one most notably being the diversity of our sample characteristics, with the inclusion of cognitively impaired and unimpaired older adults, middle-aged adults, as well as older adults with normal hearing and hearing loss. Another prominent strength of our studies was the inclusion of various training modalities, including several different physical and cognitive interventions that were completed both at-home and in a laboratory setting. Nevertheless, there are certain limitations that may constrain the interpretation of our results. Specific limitations of each of the studies are noted in their respective manuscripts, and so the following section describes limitations that generalize across the studies.

One potential limitation is that none of our analyses considered long-term follow up following the cessation of the interventions. While this was a limitation inherent to the intervention designs in Studies 1 and 2, Study 3 included a long-term follow-up, but this question was not considered in the current dissertation. There is some evidence that cognitive performance gains may be maintained following the cessation of executive function training (Nguyen et al., 2019a), physical training (Rodrigues et al., 2020), and multi-domain cognitive and physical training (Blasco-Lafargo et al., 2020). From a neural perspective, cognitive and physical training may induce differential structural and functional brain changes over the course of skill acquisition (Lövden et al., 2013; Wenger et al., 2017; Voss et al., 2010), although there is relatively little research examining neural adaptations following training cessation. As such, future research into the putative cognitive, physiological, and neural mechanisms that may contribute to the maintenance of training gains, as well as how inter-individual differences may influence maintenance versus decompensation following training cessation may be warranted.

Another potential limitation of our studies was the lack of measurement of brain morphology before and after training. Many of our interpretations were grounded in theories that suggest functional neural adaptations that occur in the context of structural brain changes (e.g., neural compensation, sensory deprivation, information degradation theories). As such, our interpretations of the functional neural mechanisms underlying or accompanying cognitive-motor dual-task improvements following training are constrained by this limitation. While there is mounting evidence to suggest a relationship between cognitive-motor dual-task performance and brain structure (Cheng et al., 2024; Hupfeld et al., 2022; Grijalva et al., 2021) and function (Holtzer et al., 2020; Maidan et al., 2016; Stojan et al., 2023) in older adults, only a few studies have examined both structural and functional brain imaging in the context of dual tasking (e.g., Holtzer et al., 2022; Ross et al., 2021). Future research including both structural and functional brain imaging following training may therefore help bolster the interpretations of our results and contribute to this growing body of knowledge.

A final potential limitation of this dissertation is the partial investigation into sex differences in cognitive-motor dual-task performance following training. While we addressed this question in Study 3, due to our smaller sample sizes in Studies 1 and 2, it was not feasible to stratify our sample into males and females, which limits the interpretation of some of our results. Specifically, we were unable to explore potential sex differences in the physiological and neural mechanisms underlying dual-task improvements following training. In addition to the known sex differences in dementia (Cao et al., 2020) and hearing loss (Pearson et al., 1995; Nolan, 2020), research also suggests that dual-task performance differs across males and females (Hollman et al., 2011; Peterson, 2022), and that sex influences the relationship between dual-task gait and cognitive decline in older adults (Christova et al., 2025). However, there have yet to be any investigations into potential sex-related differences in the mechanisms underlying training-related improvements in dual-task performance, which could be considered in future research.

Theoretical and Clinical Implications

Preserving cognitive-motor dual-task performance in older adults may be critical to mitigating functional decline, given the poor clinical outcomes associated with reduced dual-task performance in late adulthood, including increased falls risk and cognitive decline (Montero-Odasso et al., 2012b; Montero-Odasso et al., 2017; Muir-Hunter & Wittwer, 2016). The results from the studies included in this dissertation not only demonstrated improvements in cognitive-motor dual-task performance following training, but also helped in answering *why* certain interventions might be beneficial, as well as *what* interventions might be most effective in *which* individuals. Elucidating the mechanisms underlying dual-task improvements following training has both theoretical and clinical implications. Firstly, finding evidence of improved dual-task performance following interventions that specifically targeted processes that functionally overlap with our outcome measure (e.g., executive functioning, metabolic expenditure), provides compelling support for the neural overlap perspective (Lustig et al., 2009). Additionally, our research contributes empirical support for compensatory theories of cognitive aging (e.g., Park & Reuter-Lorenz, 2014), providing explicit evidence of neuroplastic changes that accompany dual-task improvements following executive function training. From a clinical perspective, elucidating the mechanisms underlying dual-task improvements following training may increase specificity of interventions designs. For example, knowledge from these studies may translate to the development of interventions that more directly target metabolic energy demands or frontal executive processes to improve cognitive-motor dual tasking.

Furthermore, our studies contribute and extend previous literature by considering the effect of inter-individual differences on dual-task performance before and after training. This work provides support for several theoretical models, including postural prioritization (Li et al., 2001; Shumway-Cook et al., 1997), compensation and magnification perspectives of training (Lövden et al., 2012), compensatory theories of cognitive aging (Park & Reuter-Lorenz, 2014), and the sensory deprivation hypothesis (Lindenberger & Baltes, 1994; Powell et al., 2022), all which appear to be mediated to some degree by inter-individual differences. Our findings may also help in the development of individualized and more specific training programs by considering individual difference factors, such as cognitive and auditory capacity, age, and sex, as well as their interactions. For example, multi-domain cognitive and physical training might be particularly beneficial for older adults with auditory and cognitive limitations, whereas single-domain aerobic exercise, coordination training, or executive function training might be sufficient in improving dual-task performance in older adults with relatively preserved cognitive and auditory functioning.

Conclusions

Overall, the current work makes several novel contributions to the field of cognitive and motor aging by elucidating the processes and factors that underlie and mediate improvements in cognitive-motor dual-task performance following cognitive and physical interventions in older adults. Specifically, we found compelling evidence for the potential mechanisms underlying cognitive-motor dual-task improvements following executive function and gross motor coordination training, as well as the effect of age, sex, and cognitive and auditory functioning on training efficacy. Importantly, the findings underscore the potential for targeted interventions to mitigate age-related declines and promote functional independence. By identifying specific mechanisms of change and individual difference factors that mediate intervention outcomes, this work not only advances our theoretical understanding of aging and cognitive-motor dual tasking but also provides actionable insights for the development of more effective, personalized intervention strategies. These contributions lay a foundation for future research aimed at optimizing cognitive and motor health in aging populations.

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Appendix A

Supplementary Material: Study 2

Model Fit Estimates for Linear Mixed Effect Models

Baseline Models

1. DV: Weighted reaction time scores
    - Fixed effects: Age nested within Age Group*Task*MoCA + MoCA*Sex + PTA*Sex + Sex*BEST + Education
    - Random effects: ID nested in Cohort
    - Marginal R^2 = 0.45, Conditional R^2 = .94

2. DV: Stride time variability
    - Fixed effects: Age Group*Task*MoCA, Task*Sex, MoCA*Sex, Age Group*BEST, Sex*BEST, Education*MoCA, Education*PTA, Education*Task
    - Random effects: ID nested in Cohort
    - Marginal R^2 = 0.37, Conditional R^2 = .94

3. DV: HbO concentration
    - Fixed effects: ROI*Condition, Hemisphere*ROI + ROI*Sex, Age nested within Age Group*Condition, Sex*MoCA + Age nested within Age Group*MoCA, + Age nested within Age Group*BEST, Education*MoCA + Sex*PTA + Education*BEST
    - Random effects: ID nested in Cohort
    - Marginal R^2 = 0.58, Conditional R^2 = .79

4. DV: Weighted reaction time dual-task cost (dual-task – single-task)
    - Fixed effects: Age nested within Age Group*HbO DTC*ROI, Age nested within Age Group*MoCA, Age nested within Age Group*PTA, Age nested within Age Group*BEST, Sex*MoCA, Sex*PTA, Sex*BEST, Education*MoCA, Education*PTA
    - Random effects: ID nested in Cohort
    - Marginal R^2 = 0.35, Conditional R^2 = .58

5. DV: Stride time variability dual-task cost (dual-task – single-task)
    - Fixed effects: HbO DTC*ROI, HbO DTC*Hemisphere, Age nested within Age Group*HbO, Age nested within Age Group*PTA, Age nested within Age Group*BEST, Sex*PTA, Education*MoCA, Education*PTA, Sex*MoCA, Education*BEST
    - Random effects: ID nested in Cohort
    - Marginal R^2 = 0.50, Conditional R^2 = .94

Training Models

1. DV: Weighted reaction time dual-task cost (dual-task – single-task)
    - To examine training effects
        1. Fixed effects: Age nested within Age Group*Intervention*Time*MoCA, Age nested within Age Group*PTA, Age nested within Age Group*BEST, Sex*MoCA, Sex*PTA, Sex*BEST, Education*MoCA
        2. Random effects: ID nested in Cohort
        3. Marginal R^2 = 0.30, Conditional R^2 = .87

    - To examine relationship with brain activity
        1. Fixed effects: Age nested within Age Group*Intervention*Time*MoCA, Education*PTA, Sex
        2. Random effects: ID nested in Cohort
        3. Marginal R^2 = 0.53, Conditional R^2 = .85

    - To examine relationship with brain activity and training improvements (Stroop switching change score from pre- to post-training)
        1. Fixed effects: Age nested within Age Group*Time*HbO DTC*StroopSwitch change score, MoCA*Time*HbO DTC*StroopSwitch change score, HbO DTC*ROI*Time, HbO DTC*ROI* Age nested within Age Group, PTA*Age nested within Age Group, Sex, Education
        2. Random effects: ID nested in Cohort
        3. Marginal R^2 = 0.42, Conditional R^2 = .87

    - To examine relationship with brain activity and training improvements (Dual-task DTC change score from pre- to post-training)
        1. Fixed effects: Age nested within Age Group*Time*HbO DTC*DTC change score, MoCA*Time*HbO DTC*DTC change score, Sex, Education, PTA*Age nested within Age Group, BEST*Age nested within Age Group
        2. Random effects: ID nested in Cohort
        3. Marginal R^2 = 0.73, Conditional R^2 = .89

2. DV: Stride time variability dual-task cost (dual-task – single-task)
    - To examine training effects
        1. Fixed effects: Age nested within Age Group*Intervention*Time*MoCA, Age nested within Age Group*PTA, Age nested within Age Group*BEST, Education*MoCA, Education*BEST, Sex
        2. Random effects: ID nested in Cohort
        3. Marginal R^2 = 0.46, Conditional R^2 = .87

    - To examine relationship with brain activity

    i. Fixed effects: Age nested within Age Group*Intervention*Time*MoCA, Age nested within Age Group*PTA, HbO DTC*ROI*Time*Training, Age nested within Age Group*BEST, Sex*MoCA, Sex*BEST, Education*MoCA, Education*BEST
    ii. Random effects: ID nested in Cohort
    iii. Marginal R^2 = 0.81, Conditional R^2 = .91

- <u>To examine relationship with brain activity and training improvements (Stroop switching change score from pre- to post-training)</u>
    i. Fixed effects: Age nested within Age Group*Time*HbO DTC*StroopSwitch change score, MoCA*HbO DTC*StroopSwitch change score, Sex, Education, Age nested within Age Group*PTA, Age nested within Age Group*BEST
    ii. Random effects: ID nested in Cohort
    iii. Marginal R^2 = 0.99, Conditional R^2 = .99

- <u>To examine relationship with brain activity and training improvements (Dual-task DTC change score from pre- to post-training)</u>
    i. Fixed effects: Age nested within Age Group*Time*HbO DTC*DTC change score, MoCA*HbO DTC*DTC change score, Sex, Education, Age nested within Age Group*PTA, Age nested within Age Group*BEST
    ii. Random effects: ID nested in Cohort
    iii. Marginal R^2 = 0.92, Conditional R^2 = .94

3. DV: HbO dual-task cost (dual-task – single-task)
    - Fixed effects: Age nested within Age Group*Intervention*Time*MoCA, Intervention*Time*ROI, Age nested within Age Group*PTA, Age nested within Age Group*BESt, Sex*PTA, Education
    - Random effects: ID nested in Cohort
    - Marginal R^2 = 0.32, Conditional R^2 = .51

4. DV: Stroop switching reaction time (from Executive Function Training evaluation sessions)
    - Fixed effects: Age nested within Age Group*Time*MoCA, Sex, Education
    - Random effects: ID nested in Cohort
    - Marginal R^2 = 0.72, Conditional R^2 = .95

5. DV: Dual-task DTCs (from Executive Function Training evaluation sessions)
    - Fixed effects: Age nested within Age Group*Time*MoCA, Sex, Education, PTA
    - Random effects: ID nested in Cohort
    - Marginal R^2 = 0.36, Conditional R^2 = .79

Appendix B

At-Home Computerized Executive-Function Training to Improve Cognition and Mobility in Normal-Hearing Adults and Older Hearing Aid Users: A Multi-Centre, Single-Blinded Randomized Controlled Trial

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Manuscript originally published in BMC Neurology. I refer to it as Downey et al. 2023 in subsequent manuscripts. Minor changes to formatting and citation style were made to make the manuscript more cohesive with the rest of the dissertation.

Abstract

Background: Hearing loss predicts cognitive decline and falls risk. It has been argued that degraded hearing makes listening effortful, causing competition for higher-level cognitive resources needed for secondary cognitive or motor tasks. Therefore, executive function training has the potential to improve cognitive performance, in turn improving mobility, especially when older adults with hearing loss are engaged in effortful listening. Moreover, research using mobile neuroimaging and ecologically valid measures of cognition and mobility in this population is limited. The objective of this research is to examine the effect of at-home cognitive training on dual-task performance using laboratory and simulated real-world conditions in normal-hearing adults and older hearing aid users. We hypothesize that executive function training will lead to greater improvements in cognitive-motor dual-task performance compared to a wait-list control group. We also hypothesize that executive function training will lead to the largest dual-task improvements in older hearing aid users, followed by normal-hearing older adults, and then middle-aged adults.

Methods: A multi-site (Concordia University and KITE-Toronto Rehabilitation Institute, University Health Network) single-blinded randomized controlled trial will be conducted whereby participants are randomized to either 12 weeks of at-home computerized executive function training or a wait-list control. Participants will consist of normal-hearing middle-aged adults (45-60 years old) and older adults (65-80 years old), as well as older hearing aid users (65-80 years old, ≥ 6 months hearing aid experience). Separate samples will undergo the same training protocol and the same pre- and post-evaluations of cognition, hearing, and mobility across sites. The primary dual-task outcome measures will involve either static balance (KITE site) or treadmill walking (Concordia site) with a secondary auditory-cognitive task. Dual-task performance will be assessed in an immersive virtual reality environment in KITE's StreetLab and brain activity will be measured using functional near infrared spectroscopy at Concordia's PERFORM Centre.

Discussion: This research will establish the efficacy of an at-home cognitive training program on complex auditory and motor functioning under laboratory and simulated real-world conditions. This will contribute to rehabilitation strategies in order to mitigate or prevent physical and cognitive decline in older adults with hearing loss.

Trial Registration: Identifier: NCT05418998. https://clinicaltrials.gov/ct2/show/NCT05418998

Key words: Hearing loss; hearing aids; aging; falls; dual-task; executive function; cognitive training; prevention; neuroimaging; virtual reality

Introduction

Background

There is a high prevalence of hearing impairment in older adults, with up to two-thirds of adults aged 70 years and older having bilateral peripheral hearing loss (Lin et al., 2011; Mick et al., 2021). Epidemiological studies have demonstrated an association between hearing loss and cognitive decline (Lin et al., 2013), incident dementia (Lin et al., 201lb; Livingston et al., 2017; 2020, Loughrey et al., 2018), frailty and increased risk of falling (Kamil et al., 2016; Lin et al., 2012), poor balance (Campos et al., 2018), and reduced gait speed (Li et al., 2013). Several mechanistic theories have been proposed to explain the association between hearing loss and cognitive decline (e.g., sensory deprivation, common cause, effortful listening; Baltes & Lindenberger, 1997; Lindenberger & Baltes, 1994). Effortful listening theories argue that when an auditory signal is impoverished due to hearing loss, increased attentional resources must be allocated to hearing, drawing on the same resources needed for other ongoing tasks requiring higher-level cognitive processing (Baltes & Lindenberger, 1997; Pichor-Fuller, 2003; Schneider & Pichora-Fuller, 2000). As higher-level cognition is involved in the regulation of posture and gait in old age (Li et al., 2018), competition for cognitive resources due to hearing loss can therefore lead to reduced performance on mobility tasks requiring attention.

Empirical evidence supporting effortful listening

Substantial evidence exists in support of effortful listening theories, including studies that compare older adults with normal hearing versus older adults with hearing loss, as well as those that manipulate the level of cognitive demand or listening effort. For example, in studies where the acoustic challenge is increased (e.g., degraded speech, speech-in-noise tasks), normal-hearing individuals exhibit greater difficulty processing linguistically complex sentences, poorer speech comprehension, and reduced memory for auditory information (Peelle et al., 2018). Additionally, studies utilizing a dual-task paradigm where a cognitive load is added to a mobility task have shown that older adults with hearing loss tend to prioritize posture or walking over cognitive performance (i.e., they have greater dual-costs in the cognitive domain; Bruce et al., 2019a; Lau et al., 2016). In concordance with effortful listening theories, this may be due to the increased attentional resources needed by older adults with hearing loss to process the auditory signal, thereby causing competition for higher level cognitive processes required during dual tasking and promoting postural prioritization to maintain safe mobility. Finally, neuroimaging studies also lend support for this theory, with increased cortical activation found in regions implicated in cognitive control (e.g., prefrontal cortex) during effortful listening in both normal-hearing adults (Davis & Johnsrude, 2003; Wong et al., 2009) and older adults with hearing loss (Campbell & Sharma, 2013; Erb & Obleser, 2013; Rosemann & Thiel, 2018). Taken together, this evidence supports effortful listening theories insofar as higher-level cognitive resources are needed to compensate for impoverished auditory inputs.

Ecologically valid measurements of hearing, cognition, and mobility

While these findings elucidate a possible mechanism underlying the association between hearing loss and cognitive and physical decline, some researchers have argued that the typical laboratory-based approaches used to measure hearing, cognition, and mobility lack ecological validity (Carpenter & Campos, 2020; Keidser et al., 2020) One method to address this issue is the use of immersive, realistic, multisensory Virtual Reality (VR) environments, which may more accurately estimate a person's cognitive, listening, or physical abilities during everyday behaviours (e.g., Lau et al., 2016, Meilinger et al., 2008; Nieborowska et al., 2018; Neider et al., 2011). Moreover, while behavioural measures of hearing ability, like pure-tone audiometry, are useful for identifying the degree of hearing loss, self-reported hearing measures may be more ecologically valid. Indeed, self-reported hearing measures often consider functional difficulties, such as fatigue due to listening effort, across a variety of settings, which may more accurately reflect everyday listening difficulties (McGarrigle et al., 2014). Utilizing such techniques is therefore critical to enhance the ecological validity of hearing, cognitive, and mobility measures.

Interventions for hearing loss

Hearing loss can begin in mid-life and has been reported to be the potentially largest modifiable risk factor for dementia (Livingston et al., 2017; 2020). Hearing aids are a readily available rehabilitation strategy used to amplify the auditory signal at differing frequencies in order to restore the audibility of sound, with demonstrated benefits in terms of improved communication (Humes et al., 2017; 2019; McArdle et al., 2005). Evidence suggests that hearing aids may improve executive functioning (Sanders et al., 2021) and speech-in-noise perception (Sanchez et al., 2020). However, more randomized controlled trials are needed to corroborate the possible benefits of hearing aids on cognition. Similarly, the current evidence for the effect of hearing aids on mobility is mixed, with a need for more well-designed randomized controlled trials (Borsetto et al., 2021). In addition to hearing aids, auditory training may be used as a rehabilitation strategy to improve speech perception through bottom-up (i.e., sensory refinement of sounds) or top-down (i.e., cognitive control) processes. A recent meta-analysis examining the pooled effect of auditory training on cognition in adults with hearing loss showed that auditory training led to transfer of learning to untrained cognitive tasks, particularly working memory and overall cognition (Lawrence et al., 2018). However, none of the reviewed studies considered motor outcomes. As such, investigations into other interventions to prevent or mitigate cognitive and physical decline in older adults with hearing loss are warranted.

Improving higher level cognition through executive function training may be particularly beneficial as it directly targets the theoretical mechanisms of effortful listening. Accumulating evidence suggests that in normal-hearing older adults, executive function training can improve cognitive, motor, and dual-task performance (Bherer et al., 2021; Desjardins-Crepeau et al., 2016; Downey et al., 2022; Fraser et al., 2017; Li et al., 2010; Pothier et al., 2021; Smith-Ray et al., 2015; Verghese et al., 2010). While more limited, there is also some evidence to suggest that combined exercise and cognitive training may benefit cognitive and motor functioning in older adults with hearing loss (Bruce et al., 2019b; Wollesen et al., 2021). Li et al. (2018) propose that cognitive interventions may increase compensatory scaffolding in response to declining motor and sensory systems with age via up-regulation of cortical activity in regions responsible for higher level cognitive functioning. However, the effect of executive function training on brain activity during dual tasking in older adults with hearing loss has yet to be examined. Additionally, while some indicators of improved cognitive/mobility-related performance have been observed following lab-based training protocols, the broad application and generalizability of these training protocols is constrained. Instead, at-home cognitive training interventions would allow for more broadly accessible and scalable solutions for cognitive training. Indeed, the

COVID-19 pandemic accelerated the development and use of tele-health applications increasing the feasibility of these approaches.

Research objectives and hypotheses

Given the association between hearing loss and cognitive and physical impairment, there is great value in identifying treatment strategies targeted at delaying or mitigating further decline. The primary objective of our research is to establish the efficacy of an at-home computerized executive function training program on complex auditory and motor functioning measured under both laboratory and simulated real-world conditions. Behavioural and neuroimaging data will be collected in middle-aged and older adults with normal hearing sensitivity thresholds, as well as older hearing aid users.

It is hypothesized that executive function training will lead to greater improvements in dual-task performance compared to no training (i.e., wait-list control group). Furthermore, it is hypothesized that the greatest improvements will be seen in older hearing aid users, followed by older adults with normal hearing, and then middle-aged adults. We also predict a differential pattern of neural plasticity as a function of age/hearing group following executive function training.

Methods

Study Design

We will conduct a multi-site, single-blinded, randomized controlled trial involving at-home executive function training over a 12-week period. A total sample of 60 participants will be recruited at each testing site, comprised of 20 middle-aged adults (aged 45-60 years old) with normal hearing, 20 older-adults (aged 65-80 years old) with normal hearing, and 20 older-adults (aged 65-80 years old) with hearing impairment who use hearing aids (with a minimum of 6 months of experience using hearing aids). Participants will be randomized to either an executive function training group or a wait-list control group. The executive function training group will complete the home-based computerized cognitive training program during a 12-week period, while the wait-list control group will not complete any form of cognitive training during the 12 weeks. Participants in the wait-list control group will be offered the cognitive training program at the end of the study. Before and after the 12 week-period, participants in both groups will be asked to complete a series of cognitive, sensory, and mobility tests during two separate in-person sessions.

Settings

Data collection will be conducted at two separate sites: Montreal (Concordia University), and Toronto (KITE-Toronto Rehabilitation Institute-University Health Network). Participants will be recruited through advertisements displayed at Concordia University's PERFORM Centre and at the Toronto Rehabilitation Institute, advertisements displayed around the Montreal and Toronto communities (e.g., hospitals, community centres), print/online advertorials targeting our target populations (e.g., Senior Times Montreal), and by contacting participants who previously completed other studies in our labs.

Participants

Participants will be asked if they were born biologically male or female and an equal number of males and females will be recruited into each group. Hearing loss is known to be more common, more severe, and has an earlier age of onset in males compared to females (Nolan, 2020; Reavis et al., 2023). A balanced design will therefore allow us to account for the known sex-related differences in hearing loss, in that we will be able to compare performance on our outcome measures across males and females.

Inclusion criteria. To be enrolled in the study, participants must be aged 45-60 years old and have normal hearing, or 65-80 years old and have either normal hearing or bilateral hearing loss and use hearing aids (with a minimum of 6-months of experience using that set of hearing aids). Hearing ability will be assessed using pure-tone audiometry. An audiometric pure tone threshold average (PTA) will be calculated for each participant across 500 Hz, 1 kHz, 2 kHz, and 4 kHz. Participants will be included in the study if they have a PTA that is equal to or below 25 dB hearing level (HL) in the better ear for the normal-hearing middle-aged and older adults, and above 25 dB HL in both ears for the older adult hearing aid users (World Health Organization, 1991). While the grades of hearing loss have recently been updated (World Health Organization, 2021), which categorize normal hearing as < 20 dB HL, we have opted to use the previous threshold of ≤ 25 dB HL for comparability with previous studies. All participants must be fluent English speakers and readers (i.e., monolingual or second language acquired early in life). Participants are also required to be physically present at Concordia University's Loyola Campus in Notre-Dame-de-Grâce, Québec, Canada or the Toronto Rehabilitation Institute, University Centre in Toronto, Ontario, Canada, for a total of four in-person assessment sessions.

Exclusion criteria. Participants will be excluded from the study if they have a learning disability, attention-deficit hyperactivity disorder, any major psychiatric illnesses (e.g., severe anxiety or depression), any previously diagnosed form of cognitive impairment, or any neurological, cardiovascular, orthopedic, or musculoskeletal conditions that may impede their mobility, concentration, or everyday functioning. Additionally, participants will be administered the Montreal Cognitive Assessment (MoCA) (Nasreddine et al., 2005), a screening tool for mild cognitive impairment. A score of 26/30 or below on the MoCA may indicate possible mild cognitive impairment (MCI). However, more recent research has shown that a cut-off of 23/30 has better diagnostic accuracy and a lower false positive rate in detecting MCI (Carson et al., 2018). As such, all participants must score above or equal to 23/30 on the MoCA, as well as perform within the age-normative range on all other neuropsychological tests (see details below). If a participant's score on the MoCA falls below 23/30, or they demonstrate below average performance on any other neuropsychological test, they will be excluded from the study. Participants must not engage in any other cognitive training programs for the entire duration of the study and must maintain a consistent physical health lifestyle (i.e., not start a new intensive strength training regime midway through the study). Participants are also required to have normal or corrected-to-normal distance visual acuity and will be excluded if they score above 0.08 on the ETDRS Visual Acuity Chart (Ferris et al., 1982), corresponding to a Snellen acuity equivalent of 20/24 or 6/7. This is an exclusion criterion as our study protocol has some visual requirements that participants need to be able to accomplish (e.g., neuropsychological testing, executive function training). Additionally, research has demonstrated that visual impairment, like hearing loss, is a potentially modifiable risk factor for dementia (Ehrlich et al., 2022), so we want to control for this possible confound. Lastly, participants exhibiting poor mobility and balance on the Mini-BESTest (Franchignoni et al., 2010), with a score falling below 16 out of 28, will not be included in the study due to an indication of potential motor difficulties (Anson et al., 2019).

Sample size. Sample size calculation is based upon prior intervention studies that utilized the same cognitive training protocol and that reported pre- and post-training changes in our primary outcome measures (e.g., gait or postural variables, auditory working memory) for healthy older adults. Specifically, Pothier et al. (2017) used the same executive function training as the current study combined with placebo stretching as one of four training groups and reported a significant Time (pre- vs. post-training) by Training Group interaction (total *n* = 90, *d* = .304, actual power = .96). For the group receiving the same cognitive training as the current study, a moderate effect of Time on gait speed was found (*n* = 23, *d* = .478), with an average increase of .13 m/s following training. Additionally, Bruce et al. (2019b) used a similar cognitive training protocol as the current study in combination with recumbent bicycling (delivered either sequentially or simultaneously), where a significant main effect of Training Group (sequential vs. simultaneous training format) was found for auditory *n*-back accuracy (*n* = 42, *d* = .718, actual power = .95). The effect size for auditory *n*-back improvement was large, whereas the effect size for gains in mobility was small to moderate. This is consistent with results from Downey et al. (2022) where the same cognitive training protocol as the current study was utilized, demonstrating a large effect size for improvements in *n*-back dual-task costs (*g* = -0.83), but a small effect size for gains in walking speed dual-task costs (g = −0.11). The recommended (G*Power) sample size to achieve a power of .95 at an alpha level of .05 for the Training Group x Time interaction for walking speed is 18 per group. Therefore, we aim to recruit 20 participants in each of the three groups (normal-hearing middle-aged adult, normal-hearing older adults, older hearing aid users) to allow for 10% attrition and a balanced design.

Measures

Primary outcome measures. The primary outcome measures will include tests of single- and dual-task cognitive, gait, and postural performance in a laboratory environment, including simulated realistic conditions. The outcome measures of interest will include cognitive accuracy and reaction times, temporal gait characteristics, posturography variables, and dual-task cost scores. The older hearing aid users will be required to wear their hearing aids during all testing procedures. Two sets of research assistants will be present at each testing site - one to work with the participant and provide instructions for the tasks, and the other to work with the technical apparatus and ensure that the data are being captured and recorded appropriately.

PERFORM Protocol at Concordia University in Montréal

Auditory 2-Back Task. An auditory 2-back task (Fraser et al., 2017) will be used to measure working memory performance under single- and dual-task conditions. Randomly ordered single digits will be presented at a rate of every two seconds, with each trial lasting 30 seconds. Single digits (1-10, excluding 7) will be presented through two loudspeakers (Logitech Z623 2.1), at ear-level in height, at a 45-degree angle relative to the listener. Using two hand-held USB response buttons (Black Box ToolKit hand-held USB response button), participants will make a button response to indicate whether the number they are currently hearing is the same or different than the number presented *n* steps previously. Response buttons will be held in both hands, with each connected to a USB response box with a 2-meter cable to allow for natural arm swing while walking. Participants will first complete an auditory 1-back task (i.e., indicate whether the number is the same or different than the number presented 1 step previously) in order to individually adjust the volume of the speakers. The decibel level will be continuously reduced until the participant is unable to attain 100 percent accuracy on the 1-back task or until they indicate that listening becomes effortful (i.e., will be asked if they needed to strain in order to understand the digits). Participants will first complete this task while standing and then while walking to ensure audibility with the added background noise of the treadmill. The amplitude of the stimuli will be set for the duration of the experiment at the decibel level from the walking trial where the participant achieved 100 percent accuracy and did not report that listening was effortful. During the 2-back task, participants will use the response buttons to indicate if the number is the same or different than the number presented 2 steps previously. Accuracy and reaction times will be measured. During the single-task 2-back condition, participants will complete the 2-back task while standing, with their feet on the sides of the treadmill. Participants will be required to hold the response buttons during the entire duration of the experiment in order to control for hand positioning but will be allowed to rest their arms on the treadmill railings during single-task 2-back conditions in order to provide postural support.

Walking Task. Participants will be required to walk on a treadmill at a self-selected speed at zero percent incline. Specifically, the speed of the treadmill will be gradually increased until the preferred speed is chosen and there are no signs of the participant sweating or being out of breath. The speed of the treadmill will be set at this speed for the duration of the experiment (i.e., will be the same speed across both single-task and dual-task conditions). During single-task conditions, participants must walk on the treadmill at their self-selected speed. During dual-task conditions, participants will simultaneously complete the 2-back task while walking. In order to measure the temporal characteristics of gait (i.e., mean and variability of step time, stride time), two electronic pressure sensors (TeleMyo Direct Transmission System) will be taped to the toe and heel of each shoe sole. Note that the treadmill will be running at the selected speed throughout the entire experiment in order to equate the same level of background noise (i.e., 50 dB SPL) across all trials.

There will three different trial types (i.e., single-task walking, single-task 2-back, dual-task) and the experiment will follow an ABC-CBA sequence, which will occur two times, for a total of 12 trials. Dual-task costs (DTC; %) will be calculated for each of the walking and 2-back tasks: [(single-task – dual-task) / single task * 100]. DTC change scores will be calculated by subtracting the post-training DTCs from the pre-training DTCs.

StreetLab Protocol at UHN/KITE in Toronto

Two dual-task paradigms will be conducted in StreetLab, a fully immersive, projection-based, VR simulator used to simulate realistic and challenging conditions (Figure 1). StreetLab has a 240° horizontal by +15° to -90° vertical field-of-view curved projection screen extending from the floor to ceiling. The virtual environment used in this study will depict a large urban 6-lane intersection street-crossing in Toronto. StreetLab is outfitted with an AMTI (Advanced Mechanical Technology, Inc., Watertown, MA) BP12001200–2000 strain gage force plate that measures ground reaction forces. There is a surround sound system with seven speakers (Meyersound MP-4XP; Meyersound Laboratories, Inc., Berkeley, CA) spatially distributed behind the projection screen, at approximately the height of a participant's head when they are standing on the force plate positioned at 0° azimuth across a horizontal plane at +/-28° (right front and left front), +/-90° (right side and left side), and +/-127° (right rear and left rear). One subwoofer (Meyersound MP-10XP) is located in the floor under the centre speaker. All speakers are 2.14m in depth from the participant when standing on the force plate (for more details of the acoustic properties of StreetLab, refer to [61]). Ambient traffic noise (e.g., vehicle traffic, bird noises) will be included to more closely simulate real-world acoustical conditions. The vehicle traffic will include moderate traffic density with approximately 10 cars appearing in the visual scene every 30 seconds. Participants will complete two dual-task paradigms that largely differ based on the two different cognitive auditory tasks to be performed, including 1) auditory 2-back task and 2) Coordinated Response Measures (CRM) task. The other primary difference from the Concordia site protocol is that instead of measuring walking as the primary mobility-related outcome measure, we will be measuring standing balance under different levels of cognitive and postural complexity.

Auditory 2-Back Paradigm. ***2-Back Task.*** The same auditory 2-back task as the Concordia site (Fraser et al., 2017) will be used; however, trials will last 60 seconds instead of 30 seconds in order to capture a sufficient amount of reliable posturography data (Carpenter & Campos, 2020). The amplitude of the loudspeakers will be individually adjusted using an auditory 1-back task to ensure optimal audibility and comfort across participants. Specifically, participants will hear 15 untimed, single digits where they will have to repeat the digit they heard out loud to the researcher immediately after the digit is presented. In order to participate in the study, participants must attain at least 70% accuracy or higher. If the amplitude is uncomfortably loud, it will be reduced (ensuring at least 70% accuracy) and the amplitude will then be set at this level for the remainder of the experiment. Accuracy and reaction time will be measured using a handheld gaming controller (Forty4 Wireless Gaming Controller). During the main experimental task, participants will make a button press indicating whether the number they are currently hearing is the same or different than the number presented *n* steps previously (i.e., 1-step previously during the practice trials, or 2-steps previously for the 2-back task). During single-task conditions, the participants will complete the 2-back while sitting on a chair on top of the force plate within StreetLab at the same approximate eye height as standing.

Postural Task. Static balance will be measured by having participants stand with their feet shoulder-width apart on a force platform. In order to control for differences in hand positions across the single-task standing and dual-task trials (since participants use handheld joysticks during the 2-back task), participants will be required to hold the joystick in the same position as the dual-task trials (but will not need to make any button responses). In order to manipulate postural load, participants with complete the standing balance task with their eyes open and eyes closed. Postural measures will include spatial (centre of pressure path length; cm), temporal (velocity; cm/s) and variability (root means square, standard deviation) measures in the anterior-posterior (front and back) and medial-lateral (side-to-side) orientations.

Overall, there will be a total of six trial types: 1) single-task 2-back eyes open, 2) single-task 2-back eyes closed, 3) single-task standing eyes open, 4) single-task standing eyes closed, 5) dual-task eyes open, 6) dual-task eyes closed. Participants will complete all trial types in an ABC-CBA sequence with the three different conditions (A: single-task standing, B: single-task 2-back, and C: dual-task). This will occur two times, once for the eyes open condition, and once for the eyes closed condition. The order of trials (i.e., eyes open vs. eyes closed) will be counter-balanced across participants. DTCs (percentage) will be calculated for both the standing and 2-back tasks: [(single-task – dual-task) / single task * 100]. DTC change scores will be calculated by subtracting the post-training DTCs from the pre-training DTCs.

CRM paradigm. ***CRM Task.*** The CRM is an auditory, multi-talker task [59], which we have adapted for use in dual-task experiments in a VR environment (Lau et al., 2012; 2016). Participants will hear two simultaneously presented, but spatially distributed sentences. Each sentence will be composed of the following structure *"Ready (callsign) go to (colour) (number) now".* A combination of 8 callsigns (Charlie, Ringo, Laker, Tiger, Arrow, Baron, Eagle, Hopper), 4 colours (red, green, white and blue) and 7 numbers (1-8 without 7) are used to compose each sentence. On each trial, a target callsign will be visually presented in text at the centre of the projection screen (e.g., Charlie). The size of a single character will be roughly 8cm x 8cm and the distance between the participant and the text will be roughly 2.1 meters. Subsequently, two sentences will be simultaneously presented from the front speaker (0 degrees) and left speaker (-90 degrees), one of which will contain the target word (e.g., the sentence "*Ready <u>Charlie</u> go to White 2 now*)". Participants will be asked to verbally repeat the colour (i.e., white) and the number (i.e., 2) associated with the target callsign sentence. The researcher will enter the participants' responses on a tablet (Samsung SM-T510). If the participant accurately repeats the colour and number, the trial is coded as correct and they receive feedback on the screen ("correct") and if either the colour, the number, or both are incorrectly reported "incorrect" is presented on the screen. For each condition (see below), five listening trials/sentences will be presented within a 60 second standing trial, which will be repeated two times per condition (10 total listening trials). During single-task conditions, the participants will complete the CRM while sitting on a chair on top of the force plate within StreetLab at the same approximate eye height as standing.

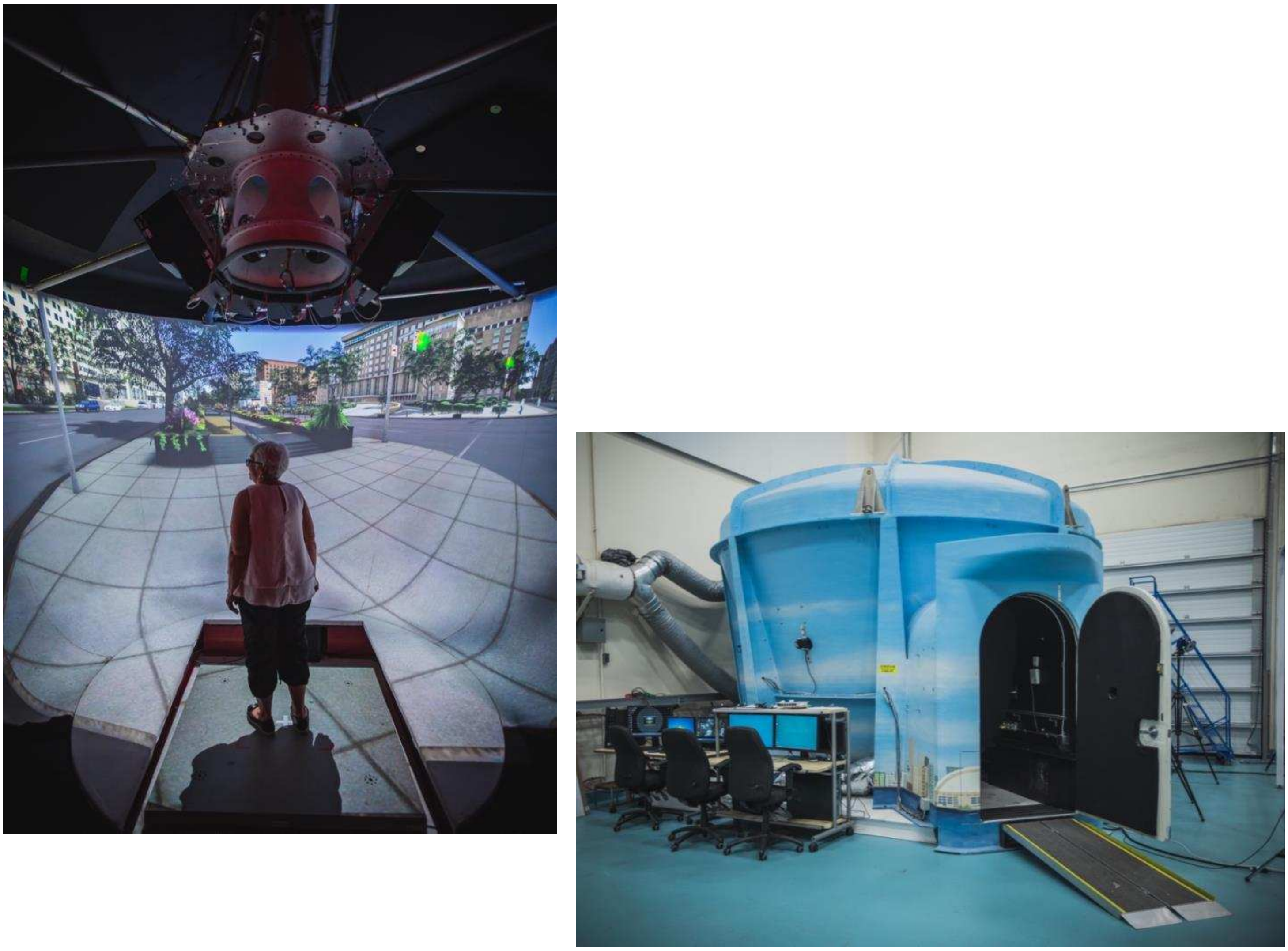
In order to manipulate attentional load and listening difficulty, we will include a block of trials in which the location of the target word will be certain 100% of the time (i.e., participants will be told the target word will always be presented at 0 degrees; termed 100% trials; lower cognitive load) and a block of trials in which the location of the target word will be uncertain, presented from the centre 60% of the time and from the left 40% of the time (i.e., participants will be told that the target word will be coming from the middle 60% of the time and from the left 40% of the time; termed 60% trials; higher cognitive load). Participants will complete these 100% and 60% trial types in single and dual-task conditions.

Postural Task. Static balance will be measured on a force platform in a semi-tandem stance, with one foot slightly in front of the other. Postural measures will include spatial (centre of pressure path length; cm), temporal (velocity; cm/s) and variability (root means square, standard deviation) measures in the anterior-posterior (front and back) and medial-lateral (side-to-side) orientations.

Overall, there will be a total of 5 different trial types: 1) single-task CRM (100%/low cognitive load), 2) single-task semi-tandem standing, 3) dual-task (60%/high cognitive load), 4) single-task CRM (60%/high cognitive load), 5) dual-task (100%/low cognitive load). Participants will complete all trial types in this order and will then repeat the trials in the reverse order, for a total of 10 trials. DTCs (percentage) will be calculated for both the standing and CRM tasks: [(single-task – dual-task) / single task * 100]. DTC change scores will be calculated by subtracting the post-training DTCs from the pre-training DTCs.

Figure 1

StreetLab



Note. Participants will either stand in the centre of the force platform with a safety harness or be seated. Under dual-task conditions, participants will be standing while concurrently performing either the auditory 2-back task or the coordinated response measures task.

Secondary outcome measures. A set of secondary outcome measures will evaluate *cognitive functioning* using a series of neuropsychological tests. The Coding subtest of the Weschler Adult Intelligent Scale (WAIS-IV) will be used as a measure of visual-motor processing speed, the Digit Span subtest - forward condition will be used to measure short term memory and the Digit Span subtest- backwards condition and Letter-Number-Sequencing subtest will be used to assess auditory working memory (Wechsler, 2008). The Trail Making Test A & B will serve to evaluate processing speed and task-switching abilities (Reitan & Wolfson, 1985). The Color Word Inference Test will be used to measure processing speed, inhibition and task-switching abilities (Delis et al., 2001). Finally, the Rey Auditory Verbal Learning Test (RAVLT) will measure participants' learning and retention of verbal information (Lezak et al., 2004). Different versions of the RAVLT, consisting of different word lists, will be administered at baseline and post-training in order to reduce possible practice effects. In order to determine whether participants fall within the age-normative range and can be included in the study, performance will be compared to normative data taken from the following sources: Wechsler et al., (2008) for the WAIS-IV measures, Delis et al., (2001) for the Color Word Interference Test, Tombaugh et al., (2004) for the Trail Making Test, and Schmidt (1996) for the RAVLT.

Secondary measures will also assess *sensory functioning* using a selection of visual and auditory tasks. For visual outcomes, the Pelli-Robson chart (Pelli et al., 1988) will be used to assess contrast sensitivity for reading letters. For auditory outcomes, the Canadian Digit Triplets Test (CDTT) (Giguére et al., 2020) will measure participants' ability to identify digits in the presence of competing noise (i.e., their speech-in-noise perception threshold). Participants will be presented with digit triplets unaided via headphones (Telephonics TDH-39P Audiometer Headset) and asked to enter their responses into a numerical keypad (Peripad-202 HW, Perixx

Computer). Pure-tone audiometry will also be conducted using a SHOEBOX Audiometer to assess participants' hearing acuity (Bastianelli et al., 2019). Participants will be presented tones via headphones (RadioEar DD450) at 250 Hz, 500 Hz, 1 kHz, 2 kHz, 4 kHz, and 8 kHz at varying decibel levels in each ear. Participants will be instructed to indicate whether they can hear the tone or not by making a button response on a tablet (iPad; Apple Inc.). Performance from tones presented at the 500 Hz, 1 kHz, 2 kHz, and 4 kHz frequencies will be averaged together to create an individual PTA for the left and right ear.

A shortened version of the Balance Evaluation Systems Test called the Mini-BESTest (Franchignoni et al., 2010) will be used to assess *motor functioning*. Postural control across four different balance control systems will be quantifiably measured, including: anticipatory transition (e.g., going from sitting to standing), reactive postural control (e.g., leaning outside one's centre of pressure and compensating for a loss of balance), sensory orientation (e.g., balancing with eyes closed or on a compliant surface), and dynamic gait (e.g., walking while turning head, changing speed, or stepping over obstacles).

A set of questionnaires will also be given to participants to complete online using Qualtrics survey software (Qualtrics, Provo, Utah) in order to assess *subjective functioning* across cognitive, hearing, and mobility domains. Specifically, within the domain of cognition, the Frequency of Forgetting Questionnaire (FFQ) will be used to assess subjective memory abilities and how frequently one forgets things in everyday life (Zelinski & Gilewski, 2004). In the domain of hearing, the Listening Self-Efficacy Questionnaire (LSEQ) will be used to assess one's self-efficacy or confidence in understanding speech in a variety of listening situations (Smith et al., 2011), and the Hearing Handicap Inventory Screening Questionnaire for the Elderly (HHIE-S) will be given to assess self-reported experiences of hearing difficulties in everyday life (Weinstein & Ventry, 1983). Within the domain of motor functioning, the Activities-Specific Balance Confidence (ABC) Scale will be used to determine participants' balance efficacy (Powell & Myers, 1995). Additionally, participants will be asked to complete the Everyday Activity Questionnaire (EAQ), which samples a broad range of activities relevant to older adults' lives (maintenance of self and property, social, leisure, religious, and creative activities) (Arbuckle et al., 1994). Lastly, the Social Disengagement Inventory (SDI) will be used to measure how participants interact and engage with their social environment (Bassuk et al., 1999).

Brain activity will be measured (Pre- and Post-Training) using functional near infrared spectroscopy (fNIRS) at Concordia's PERFORM Centre. The working brain is in constant need of supply of glucose and oxygen for efficient functioning. As such, levels of oxygenated hemoglobin (HbO) and deoxygenated hemoglobin (HbR) in the brain can be used as neurobiological indicators of cortical activation. Increased brain activation leads to increased blood volume and blood flow, resulting in an increase in HbO and a decrease in HbR. Conversely, decreased brain activation leads to decreased blood volume and blood flow, resulting in a decrease in HbO and an increase in HbR. Functional near infrared spectroscopy provides a non-invasive measure of HbO and HbR fluctuations in the cerebral cortex with high temporal resolution (Jobis, 1977). A mobile (wireless/Bluetooth) fNIRS device will be used to allow participants to freely complete the experimental task while walking (Artinis Brite MKIII, Netherlands). Light optode placement will follow a 24-channel frontal template provided by the analysis software OxySoft (Version 3.3.30). Data pre-processing involving the visual inspection of motion artifacts, detection of bad channels, Modified Beer-Lambert Law (MBLL) conversion, and band pass filtering (0.005Hz-0.1Hz), will be conducted using MATLAB (Version R2021b) and the open-source application Brainstorm (Tadel et al., 2011). Additionally, all trials will be normalized to baseline, which will be taken during a quiet standing condition prior to each trial. A single HbO activation average will be computed for each participant for each trial type (i.e., single-task walking, single-task 2-back, and dual-task). HbO change scores will then be derived to compare Pre- and Post-Training cortical activation levels.

Study Procedure

Prior to any in-person visit, a telephone screening will be conducted to determine a participant's initial eligibility to participate in the study (i.e., will gather demographic information and a basic medical history, as well as the participant's comfort level using a computer or tablet). Eligible participants will be asked to come into Concordia University's Loyola Campus (Montreal location) or KITE-Toronto Rehabilitation Institute, University Health Network (University Centre location) to provide written consent, be further screened using a more in-depth health history interview, and be assessed on various cognitive and sensory measures, including pure-tone audiometry, CDTT, MoCA, Pelli-Robson Contrast Sensitivity, RAVLT, Coding, Digit Span, Trail Making Test A & B, Letter-Number-Sequencing, and Color Word Inference Test (Pre-Training Session 1). Testing will take place in a quiet, well-illuminated room. If deemed eligible, participants will be asked to come into Concordia University's PERFORM Centre (Montreal location) or KITE-Toronto Rehabilitation Institute, University Health Network (University Centre) to assess our primary outcome measure (i.e., cognitive-motor dual tasking) and other measures including the ETDRS and Mini-BESTest (Pre-Training Session 2). Participants will also be asked to complete a series of questionnaires online between Pre-Training Sessions 1 and 2 (i.e., LSEQ, ABC, EAQ, FFQ, HHIE-S, SDI). Participants will then be randomized into either the executive function training group or the wait-list control group. The executive function training group will receive a virtual tutorial session on how to use the at-home cognitive training program. Participants will then undergo either 12 weeks of cognitive training or will continue their life as usual (wait-list control group). Both groups will be called once a week to keep track of any changes in lifestyle, stress, energy levels or any other important life events. The executive function training group will also be asked about their training that week (e.g., if they are having any difficulty with the training or need further clarification, if they are noticing any progress/improvements, if they are experiencing any technical issues, if they missed a session). Following the 12-week period, all participants will be invited back to complete the same sensory, cognitive, and motor assessments that they completed at baseline (Post-Training Session 1 and Post-Training Session 2). Participants will also complete the LSEQ, ABC, and FFQ questionnaires again to measure changes in subjective hearing, mobility, and cognition, respectively. An overview of the study procedure across each testing site is shown in Figure 2.

Randomization. Upon completion of the screening and baseline assessments, participants will be randomized to either the executive function training or wait-list control group. Randomization of participants will be completed within each of the three groups (i.e., middle-aged, older adults, hearing aid users) using a computerized random number generator. Final cohorts will be semi-randomized in order to attain an equal number of participants in the training and control groups and to balance the number of males and females within each age/hearing group.

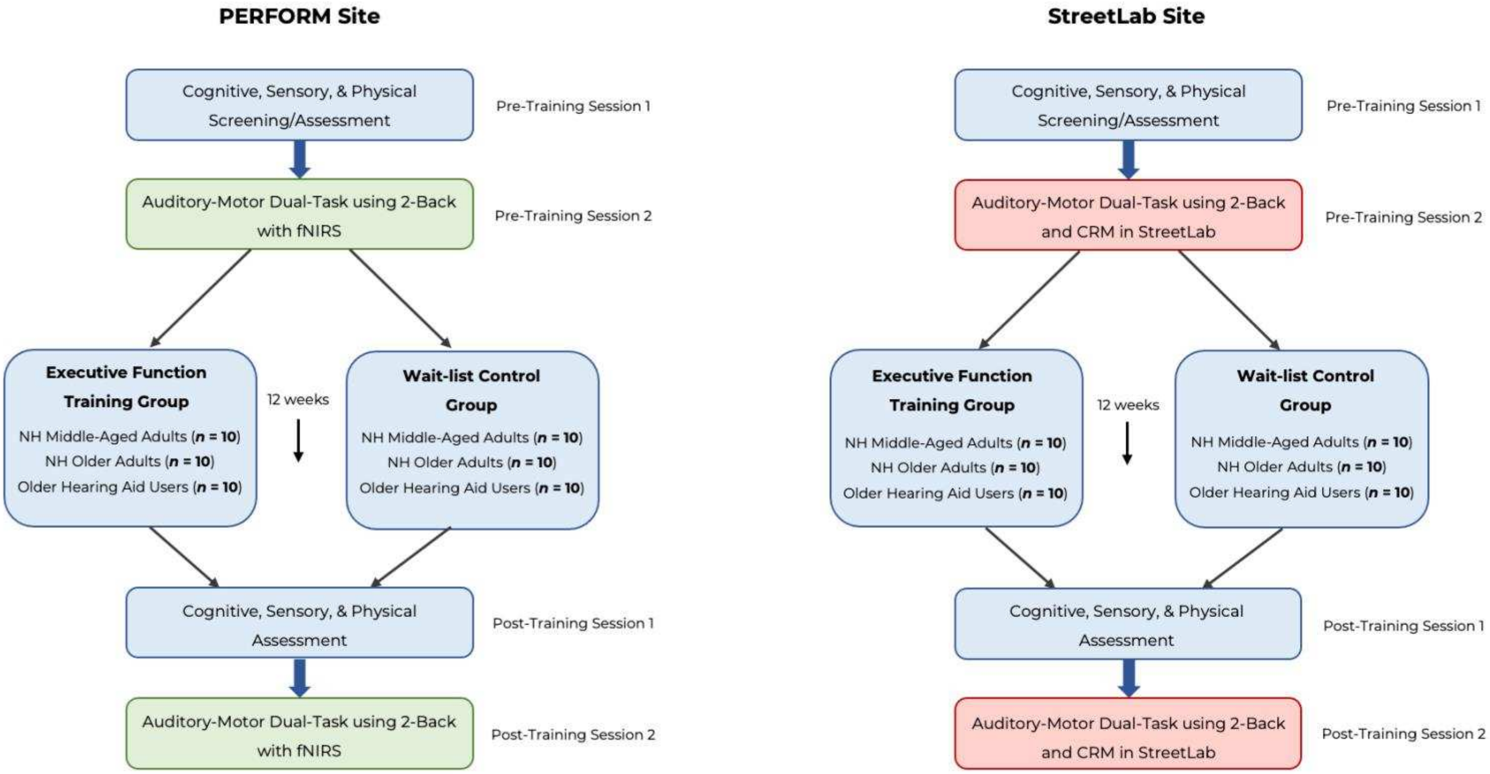
Blinding. Participants will be made aware of the two groups in which they could be randomized to and will know which of the two groups they have been assigned to following the baseline assessments. Efforts will be made so that the evaluators conducting the Pre- and Post-

Training assessments will be blind to the participants' randomization status. For example, the research personnel responsible for calling participants during the 12-week period will be different than the research personnel completing the post-training evaluations.

Ethical Considerations. Each intervention site obtained approval by their corresponding Research Ethics Board prior to initiating any study-related activities, including Concordia University's Human Research Ethics Committee (Certificate #30011799) and KITE-Toronto Rehabilitation Institute-University Health Network (REB#19-5857).

Figure 2

Flowchart of Measures and Timeline of our Multi-Site, Single-Blinded, Randomized Controlled Trial



Note. Each site will be comprised of a sample of 20 middle-aged adults and 20 older adults with normal hearing (NH), as well as 20 older adults with age-related hearing loss who use hearing aids. An equal number of males and females will be recruited into each training group within each of the age/hearing groups. Both the executive function training group and wait-list control group will participate in Pre- and Post-Training assessments. During the 12-week intervention phase, the executive function training group will complete an at-home cognitive training program three times a week (30 minutes/session). The wait-list control group will not complete any form of cognitive training during the duration of the experiment, but will be offered the materials at the end of the study.

Interventions

At-home executive function training group. After the Pre-Training phase, participants randomized to the executive function training group will complete an at-home computerized cognitive training program three times a week for a total of 12 weeks (each session lasting 30 minutes). The training protocol will involve a custom-written program that has been used in previous research studies assessing cognitive and gait outcomes, but was previously administered in a controlled laboratory environment (Desjardins-Crepeau et al., 2016; Fraser et al., 2017; Pothier et al., 2021). Specifically, the training is comprised of three distinct modules (Stroop, dual-task, *n*-back), which aim to improve different aspects of executive functioning such as inhibition and task switching-abilities, divided attention, and working memory, respectively. Participants will be encouraged to evenly disperse the training throughout the week (i.e., 48 hours between sessions). However, participants have the flexibility to complete the sessions according to their own schedule. Each training session (30 minutes) is comprised of two different modules (each 15 minutes). Participants may take a break between modules, but not during a module. The computerized program can be completed on either a laptop, desktop, or tablet, but should be held consistent throughout the 12-week duration of the training. Participants will also be instructed to work as fast as they can without making any mistakes, as both reaction time (milliseconds) and accuracy will be recorded for all three tasks. After each session, a performance feedback graph will be presented to provide encouragement and allow participants to track their progress.

The Stroop module aims to improve inhibition and task-switching using four separate conditions (familiarization, reading, inhibition, and switching) presented at different points throughout the training period. Participants will be required to press the appropriate letter key on their keyboard or press the appropriate button on their tablet, based on the condition presented. In the familiarization condition, a single letter will be presented on the screen. In the reading condition, asterisks will form a letter on the screen. In the inhibition condition, smaller letters will make up a larger letter (e.g., copies of small letters “L” to form a larger “H”), and participants will need to inhibit the automatic response of indicating what the smaller letter is, and instead indicate what larger letter is formed. In the switching condition, participants will need to alternate between reporting the smaller letters presented, or the larger letters that are formed, depending on the goal as indicated by whether a white frame is surrounding the group of letters or not.

The visual *n*-back module targets the updating and maintenance of information in working memory. Participants will be instructed to make a keyboard response or button press on a tablet indicating whether the letter they see is the same or different from the one presented one previously (1-back), two previously (2-back), or three previously (3-back). The more challenging 2-back and 3-back trials will make up a larger proportion of the trial type distribution as the training progresses in order to enhance the difficulty level. Of note, the modality of the *n*-back in the cognitive training differs from the modality used in the dual-task experiment (i.e., visual during training versus auditory during the dual-task experiment).

The dual-task module aims to improve divided attention. Participants will complete a visual discrimination task whereby they will need to make a response to one type of image (single-task; i.e., modes of transportation or fruits;) or two types of images concurrently (dual-task; i.e., one image reflecting a mode of transportation and another image of a fruit). Participants will complete pure blocks of only single-task trials (single-pure trials) or only dual-task trials (dual-pure trials) or will complete mixed blocks that randomly involve one (single-mixed trials) or both tasks (dual-mixed trials). For the dual-task trials, participants will be instructed to respond to both stimuli equally. However, as the training progresses, participants will need to prioritize one hand over the other to increase the level of difficulty (i.e., in the dual-task trials when two images are presented, participants will be asked to make a response using their left or right hand first before making a response with the other hand).

Waitlist control group. Participants randomized to the wait-list control group will complete both the Pre- and Post-Training assessments but will not partake in any form of cognitive training during the 12-week period. Weekly phone calls will ensure that participants are maintaining a consistent lifestyle and that they are not starting any other cognitive training programs. The weekly phone calls will also allow for a similar level of social interaction amongst the research personnel and the participants across the wait-list control and training groups in order to control for this possible confound. Upon completing the study, the wait-list control group will be offered the materials for the at-home executive function training program, and researchers will be available to offer assistance if needed.

Data Analysis

All data analyses will be completed using IBM SPSS Statistical Software and/or R. Data will be screened and corrected for normality, outliers, and missing values. Descriptive statistics (e.g., means and standard deviations for continuous variables; frequencies and percentages for categorical variables) will be presented for the demographic and baseline characteristics. Chi square tests (for categorical variables) or One-Way ANOVAs (for continuous variables) will be used to determine if there are any differences between groups at baseline (i.e., middle-aged vs. older adults vs hearing aid users; training vs. control groups).

In order to evaluate our primary hypothesis (i.e., that executive function training will lead to greater improvements in dual-task performance compared to a wait-list control group), separate 3 x 2 x 2 Mixed Factorial ANOVAs will be conducted for each of the primary outcome measures (i.e., 2-back accuracy and reaction times, CRM accuracy, temporal gait parameters, posturography variables, DTC scores), whereby the Between-Subjects factors will include Age/Hearing Group (middle-aged, older adult, hearing aid users) and Training Group (cognitive training, control), the Within-Subject factor will include Time (pre- vs. post-evaluations), and Covariates will include sex and education. Observation of a statistically significant Time by Training Group interaction in any of the primary outcome measures will be considered preliminary evidence for training efficacy. In order to examine our second and third hypotheses (i.e., that largest improvements in dual-task performance and greatest augmentation of brain activity will be found in older hearing aid users, followed by normally-hearing older adults, and then middle-aged adults) separate One-Way ANOVAs will be used on the dual-task and HbO change scores within the cognitive training group, whereby the Between Subjects factor will include Age/Hearing Group (middle-aged, older adult, hearing aid users). Observation of a statistically significant main effect of Group will be followed up by *post hoc* pairwise analyses with Bonferroni corrections in order to determine whether our hypotheses are supported.

Linear mixed effects models will also be fitted for each of our outcome measures, particularly if there is a large amount of missing data or if there is an unequal amount of variance across groups. Specifically, Fixed effects will include Age/Hearing Group (middle-aged, older adult, hearing aid users), Training Group (executive function training, control), Sex (male/female), and Time (Pre- vs. Post-Training), Random effects will include the individual participants, and Covariates will include education.

Lastly, in order to elucidate whether brain activity reflects neural compensation or inefficiency, correlations between dual-task performance and HbO levels will be conducted at baseline and after 12 weeks. All statistical tests will be two-tailed, and a *p*-value of less than 0.05 will be considered to indicate statistical significance. Effect sizes will be calculated using Hedges' *g*.

Discussion

In this multi-site single-blinded randomized controlled trial, we aim to establish the efficacy of an at-home cognitive training program aimed at improving cognitive and motor functioning under laboratory and simulated real-world conditions in normal-hearing middle aged and older adults and older hearing aid users. We hypothesize that executive function training will lead to greater improvements in dual-task performance compared to a wait-list control group. Moreover, we hypothesize that executive function training will lead to the largest dual-task improvements in older hearing aid users, followed by normal-hearing older adults, and then middle-aged adults. Lastly, we predict a differential pattern of neural plasticity as a function of age/hearing group following executive function training.

Computerized executive function training has been shown to improve cognition and mobility in normal-hearing older adults (Bherer et al., 2021; Desjardins-Crepeau et al., 2016; Downey et al., 2022; Fraser et al., 2017; Li et al., 2010; Pothier et al., 2021; Smith-Ray et al., 2015; Verghese et al., 2010). Preliminary evidence also suggests that combined exercise and cognitive training can improve dual-task performance in older adults with hearing loss (Bruce et al., 2019b; Wollesen et al., 2021). However, further research is needed to investigate the effect of executive function training (in isolation rather than combined with exercise) on cognition and mobility in older adults with hearing loss. Additionally, as telehealth has been increasingly utilized since the COVID-19 pandemic, it is paramount to explore whether similar results remain when cognitive training is completed remotely, rather than in a laboratory setting.

Our study aims to fill these gaps in knowledge and will be the first of its kind to examine the effect of an at-home executive function training program on complex auditory and motor performance in normal-hearing middle-aged and older adults and older hearing aid users. One advantage of our study protocol includes the targeted population given that hearing loss is associated with an increased risk for falls and dementia, which may be modified through hearing aids and cognitive training. We will also recruit normal-hearing middle-aged and older adults in order to examine differences in cognition and mobility that can occur with age and changes in hearing acuity.

Another strength of the study protocol is the use of ecologically valid measurement techniques, including subjective and objective measures of hearing, cognition, and mobility, as well as an immersive, multisensory VR environment to assess realistic sensory-cognitive-motor challenges. Our previous research assessing dual-task performance in a simulated street crossing environment showed that older adults tended to prioritize posture over cognitive performance (e.g., reduced gait variability at the cost of word recognition accuracy; Lau et al., 2016; Nieborowska et al., 2018). As such, our study will add to this growing literature and extend previous research using traditional laboratory-based experiments.

A final strength of the protocol is the use of portable fNIRS to examine brain activity in the prefrontal cortex during dual-task walking before and after training. Currently, there are inconsistent findings with regard to the effect of dual tasking on brain activity across younger and older adults, with some researchers showing a bilateral upregulation in the prefrontal cortex in older adults compared to younger adults (Mirelman et al., 2017; Ohsugi et al., 2013), others showing comparable brain activity (Fraser et al., 2016), and others showing greater activity in younger adults compared to older adults (Holtzer et al., 2011). It also remains unclear how brain activity during dual tasking changes following cognitive training. Scaffolding theories propose that training may increase compensatory mechanisms in response to declining brain structure with age via an up-regulation of frontal brain regions (Reuter-Lorenz & Park, 2014). However, the effect of cognitive training on brain activity during dual tasking in older adults with hearing loss has yet to be examined. We therefore hope that our study will elucidate some of these inconsistencies and contribute to the growing knowledge on mobile brain imaging.

In conclusion, this research will help establish the efficacy of an at-home cognitive training program in improving cognitive and motor functioning in older adults with hearing loss. Given the association between hearing loss and dementia and falls risk, the results of this study may have direct implications for older adults, in terms of improving quality of life and level of autonomy, as well as potentially reducing healthcare costs. Indeed, dementia and falls cause $10.4 and $2 billion a year in healthcare costs, respectively (Chambers et al., 2016; SMARTRISK, 2009). From a basic science perspective, this research will also contribute to our understanding of how brain activity differs amongst normal-hearing middle-aged and older adults, and older hearing aid users, as well as how brain activity changes in response to cognitive training. These findings will elucidate whether brain activity reflects a compensatory mechanism for declining brain structure due to age and hearing loss, or whether it is a marker of neural inefficiency that can be improved through cognitive training.

Appendix C

Exploratory Analyses Following Study 2

As a follow-up to study 2, we conducted exploratory analyses to examine differences in cognitive-motor dual-task performance and brain activity before and after executive function training in older adults with normal hearing ($n = 23$) versus older adults with hearing loss who were experienced hearing aid users ($n = 11$). At baseline, we found that the hearing aid users were significantly older, had significantly poorer peripheral and central hearing, and had significantly poorer balance performance, compared to the older adults with normal hearing (Table 1). No significant differences were observed across hearing groups on any of the primary outcome measures (i.e., single- and dual-task cognitive and gait performance, HbO levels).

In investigating the relationship between changes in behavioural performance and brain activity (Δ *Activation*) from single-task to dual-task at baseline and whether this relationship varied as a function of hearing ability, we found a significant PTA by Δ *Activation* interaction on cognitive DTCs, $t(142.00) = -2.01$, $p = .046$, $f^2 = .02$. Specifically, in participants with poorer hearing (i.e., PTA $\geq$ 35 db HL), a greater increase in HbO levels from single-task to dual-task predicted lower cognitive DTCs (B = -13.01, $SE = 3.83$, $p = .001$). We further found a significant PTA by Δ *Activation* interaction on gait DTCs, $t(136.00) = 3.72$, $p < .001$, $f^2 = .10$, such that in individuals with better hearing (i.e., PTA < 20 db HL), higher HbO levels from single-task to dual-task predicted lower cognitive DTCs (B = -.008, $SE = .002$, $p = .001$). There were no significant interactions observed between Δ *Activation* and hearing group.

In investigating the association between changes in dual-task performance and brain activation following executive function training or a wait-list control, and whether this relationship varied as a function of hearing ability, we found a significant Time by Training

Group by PTA by Δ *Activation* interaction on cognitive DTCs, $F(1, 273.28) = 17.61$, $p < .001$, $\eta_p^2 = .06$. Specifically, in participants with poorer hearing (i.e., PTA ≥ 35 db HL), the slope between Δ *Activation* and cognitive DTCs significantly increased following the Control (i.e., at baseline, higher Δ *Activation* predicted lower DTCs: $B = -9.03$, $SE = 4.31$, $p = .037$, and post-training, higher Δ *Activation* predicted higher DTCs: $B = 7.65$, $SE = 3.45$, $p = .027$).

Regarding the relationship between gait DTCs and brain activity following training across hearing ability, we found a significant Time by Training Group by PTA by Δ *Activation* interaction, $F(1, 269.64) = 7.08$, $p = .008$, $\eta_p^2 = .03$. Specifically, in participants with poorer hearing (i.e., PTA ≥ 35 db HL), the slope between Δ *Activation* and gait DTCs significantly decreased following EF training (i.e., at baseline, there was no significant relationship between Δ *Activation* and gait DTCs, and post-training, higher Δ *Activation* marginally predicted lower DTCs: $B = -.002$, $SE = .001$, $p = .063$). In contrast, in participants with better hearing (i.e, PTA ≤ 20 db HL), the slope between Δ *Activation* and gait DTCs significantly increased following the Control (i.e., at baseline, higher Δ *Activation* predicted lower DTCs: $B = -.007$, $SE = .001$, $p < .001$, and post-training, higher Δ *Activation* predicted higher DTCs: $B = .002$, $SE = .001$, $p = .040$). There were no significant interaction effects between Δ *Activation* and hearing group following training.

Table 1

Descriptive Statistics and Independent Sample T-Tests/Chi Square Tests for Participant Characteristics and Primary Outcome Measures Across Normal-Hearing Older-Adults and Older Hearing Aid Users at Baseline

Variable	Normal Hearing Older Adults			Older Hearing Aid Users			*t or* χ^2	*p*	*d*
	n	*M*	*SD*	*n*	*M*	*SD*			
Age (years)	23	70.61	3.07	11	73.27	4.43	-2.05	.049	-.75
Education (years)	23	17.39	3.36	11	17.82	4.77	-.30	.765	-.11
MoCA (/30)	23	26.26	1.79	11	25.36	2.62	1.17	.249	.43
Mini-BESTest (/28)	23	21.13	3.97	11	15.91	4.04	3.57	<.001	1.31
PTA (db HL)	23	12.57	4.02	11	49.63	11.56	-9.88	<.001	-5.23
CDTT SRT (SNR)	22	-11.03	1.01	11	-4.58	2.36	-8.67	<.001	-4.09
ST RTW (ms)	23	1240.67	159.48	11	1257.12	182.09	-.27	.790	-.10
DT RTW (ms)	23	1272.16	130.64	11	1302.07	177.43	-.56	.582	-.20
ST Stride Time Variability (SD)	16	.14	.11	8	.10	.11	.86	.397	.37
DT Stride Time Variability (SD)	16	.14	.11	8	.09	.10	1.17	.276	.48
ST Cog HbO (µmol/L)	21	4.24	3.09	6	3.84	2.47	.81	.422	.20
ST Gait HbO (µmol/L)	21	3.78	3.70	6	3.58	4.00	.27	.791	.06
DT HbO (µmol/L)	21	5.40	4.08	6	5.90	3.16	-.78	.437	-.20
Sex (*n female, %*)	23	13 (56.5)		11	6 (54.5)		.012	.914	

Note. MoCA = Montreal Cognitive Assessment; BEST = Balance Evaluation Systems Test; PTA = Pure Tone Average; db HL = Decibels hearing level; CDTT SRT = Canadian Digit Triplet Test – Speech Response Threshold; SNR = Signal to noise ratio. ST = Single-task; DT = Dual-task; RTW = Weighted reaction time (combination of accuracy and speed performance); HbO = Oxyegnated hemoglobin.

Appendix D

Supplementary Material: Study 3

Methods

Background measures. An abbreviated pure-tone audiometry assessment was conducted as a screening procedure in the COMPASS-ND study using a GSI 18 audiometer in a quiet clinical examination room. Participants were assigned to one of two hearing loss categories based on their ability to detect 2-kHz pure tones. Participants who were able to detect a 2-kHz tone at 25 dB HL on at least one trial in either one or both ears were assigned to category 1 (“Normal Hearing”), whereas participants who were unable to detect a 2-kHz tone at 25 dB HL in both ears were assigned to category 2 (“Hearing Impaired”). This methodology has been validated in a previous study examining the effect of hearing loss on cognition in MCI participants using data from the COMPASS-ND study (Al-Yawyer et al., 2022).

Statistical Analyses

The factors included in each linear mixed model, as well as the model fit estimates, for each outcome measure at baseline and following training are described below. Note that conditional R^2 indicates the amount of variance explained by both fixed and random factors, while marginal R^2 indicates the amount of variance explained by only the fixed factors.

Baseline models

Cognitive accuracy. The selected mixed effect model (conditional $R^2 = 0.73$, marginal $R^2 = 0.66$) to examine whether hearing loss severity (as measured with HHIE) significantly predicted cognitive accuracy at baseline (Hypothesis 1) included the following fixed effects: HHIE x Condition, HHIE x Sex, HHIE x Education, Condition x Education, and MoCA x Age, and the following random intercepts: Subject nested within Testing Site. The selected mixed effect model (conditional $R^2 = 0.72$, marginal $R^2 = 0.64$) to examine whether hearing loss severity (as measured with CDTT) significantly predicted gait speed at baseline (Hypothesis 1) included the following fixed effects: CDTT x Condition, CDTT x Sex, Age, MoCA, and Education, and the following random intercepts: Subject nested within Testing Site.

Gait speed. The selected mixed effect model (conditional $R^2 = 0.89$, marginal $R^2 = 0.17$) to examine whether hearing loss severity (as measured with HHIE) significantly predicted gait speed at baseline (Hypothesis 1) included the following fixed effects: HHIE x Condition, HHIE x MoCA, Age, Education, and Sex, and the following random intercepts: Subject nested within Testing Site. The selected mixed effect model (conditional $R^2 = 0.90$, marginal $R^2 = 0.23$) to examine whether hearing loss severity (as measured with CDTT) significantly predicted gait speed at baseline (Hypothesis 1) included the following fixed effects: CDTT x Condition, CDTT x MoCA, Age, Education, and Sex, and the following random intercepts: Subject nested within Testing Site.

Stride time. The selected mixed effect model (conditional $R^2 = 0.89$, marginal $R^2 = 0.16$) to examine whether hearing loss severity (as measured with HHIE) significantly predicted stride time at baseline (Hypothesis 1) included the following fixed effects: HHIE x Condition, HHIE x MoCA, Age, Education, and Sex, and the following random intercepts: Subject nested within Testing Site. The selected mixed effect model (conditional $R^2 = 0.89$, marginal $R^2 = 0.25$) to examine whether hearing loss severity (as measured with CDTT) significantly predicted stride time at baseline (Hypothesis 1) included the following fixed effects: CDTT x Condition, CDTT * MoCA, Age, Education, and Sex, and the following random intercepts: Subject nested within Testing Site.

Stride time variability. The selected mixed effect model (conditional $R^2 = 0.37$, marginal $R^2 = 0.15$) to examine whether hearing loss severity (as measured with HHIE) significantly predicted stride time variability at baseline (Hypothesis 1) included the following fixed effects: HHIE x Condition, MoCA x Age, Education, and Sex, and the following random intercepts: Subject nested within Testing Site. The selected mixed effect model (conditional $R^2 = 0.33$, marginal $R^2 = 0.13$) to examine whether hearing loss severity (as measured with CDTT) significantly predicted stride time variability at baseline (Hypothesis 1) included the following fixed effects: CDTT x Condition, MoCA x Age, Education, and Sex, and the following random intercepts: Subject nested within Testing Site.

Stride length. The selected mixed effect model (conditional $R^2 = 0.89$, marginal $R^2 = 0.20$) to examine whether hearing loss severity (as measured with HHIE) significantly predicted stride length at baseline (Hypothesis 1) included the following fixed effects: HHIE x Condition, Age x Condition, MoCA, Education, and Sex, and the following random intercepts: Subject nested within Testing Site. The selected mixed effect model (conditional $R^2 = 0.94$, marginal $R^2 = 0.19$) to examine whether hearing loss severity (as measured with CDTT) significantly predicted stride length at baseline (Hypothesis 1) included the following fixed effects: CDTT x Condition, Age x Condition, MoCA Education, and Sex, and the following random intercepts: Subject nested within Testing Site.

Stride length variability. The selected mixed effect model (conditional $R^2 = 0.32$, marginal $R^2 = 0.14$) to examine whether hearing loss severity (as measured with HHIE) significantly predicted stride length variability at baseline (Hypothesis 1) included the following fixed effects: HHIE x Condition, HHIE x MoCA, Age x Condition, Education, and Sex, and the following random intercepts: Subject nested within Testing Site. The selected mixed effect model (conditional $R^2 = 0.30$, marginal $R^2 = 0.20$) to examine whether hearing loss severity (as measured with CDTT) significantly predicted stride length variability at baseline (Hypothesis 1) included the following fixed effects: CDTT x Condition, MoCA x CDTT, CDTT x Age, CDTT x Education, and Sex, and the following random intercepts: Subject nested within Testing Site.

Double support time. The selected mixed effect model (conditional $R^2 = 0.85$, marginal $R^2 = 0.16$) to examine whether hearing loss severity (as measured with HHIE) significantly predicted double support time at baseline (Hypothesis 1) included the following fixed effects: HHIE x Condition, Age x MoCA, Education, and Sex, and the following random intercepts: Subject nested within Testing Site. The selected mixed effect model (conditional $R^2 = 0.85$, marginal $R^2 = 0.33$) to examine whether hearing loss severity (as measured with CDTT) significantly predicted double support time at baseline (Hypothesis 1) included the following fixed effects: CDTT x Condition, CDTT x MoCA, CDTT x Age, MoCA x Age, Education, and Sex, and the following random intercepts: Subject nested within Testing Site.

Training models

Cognitive performance. The selected mixed effect model (conditional $R^2 = 0.73$, marginal $R^2 = 0.66$) to examine whether hearing loss severity (as measured with HHIE) significantly predicted degree of improvement in cognitive accuracy following training (Hypothesis 2) included the following fixed effects: HHIE x Training, HHIE x Education, HHIE x Condition, HHIE x Sex, Education x Condition, and MoCA x Age, and the following random intercepts: Subject nested within Testing Site. The selected mixed effect model (conditional $R^2 = 0.70$, marginal $R^2 = 0.64$) to examine whether hearing loss severity (as measured with CDTT) significantly predicted degree of improvement in cognitive accuracy following training (Hypothesis 2) included the following fixed effects: CDTT x Training x Time, CDTT x Sex, Age, Education, MoCA, and Condition, and the following random intercepts: Subject nested within Testing Site.

Gait speed. The selected mixed effect model (conditional $R^2 = 0.83$, marginal $R^2 = 0.26$) to examine whether hearing loss severity (as measured with HHIE) significantly predicted degree of improvement in gait speed following training (Hypothesis 2) included the following fixed effects: HHIE x Training, HHIE x Sex, Age, Education, MoCA, and Condition, and the following random intercepts: Subject nested within Testing Site. The selected mixed effect model (conditional $R^2 = 0.83$, marginal $R^2 = 0.30$) to examine whether hearing loss severity (as measured with CDTT) significantly predicted degree of improvement in gait speed following training (Hypothesis 2) included the following fixed effects: CDTT x Training x Time, CDTT x MoCA, Age, Sex, Education, and Condition, and the following random intercepts: Subject nested within Testing Site.

Stride time. The selected mixed effect model (conditional $R^2 = 0.80$, marginal $R^2 = 0.19$) to examine whether hearing loss severity (as measured with HHIE) significantly predicted degree of improvement in stride time following training (Hypothesis 2) included the following fixed effects: HHIE x Training x Time, HHIE x Sex, Age, Education, MoCA, and Condition, and the following random intercepts: Subject nested within Testing Site. The selected mixed effect model (conditional $R^2 = 0.79$, marginal $R^2 = 0.32$) to examine whether hearing loss severity (as measured with CDTT) significantly predicted degree of improvement in stride time following training (Hypothesis 2) included the following fixed effects: CDTT x Training x Time, CDTT x Sex, CDTT x MoCA, Education x MoCA, Age, and Condition, and the following random intercepts: Subject nested within Testing Site.

Stride time variability. The selected mixed effect model (conditional $R^2 = 0.37$, marginal $R^2 = 0.13$) to examine whether hearing loss severity (as measured with HHIE) significantly predicted degree of improvement in stride time variability following training (Hypothesis 2) included the following fixed effects: HHIE x Training x Time, MoCA x Education, Age, Sex, and Condition, and the following random intercepts: Subject nested within Testing Site. The selected mixed effect model (conditional $R^2 = 0.31$, marginal $R^2 = 0.10$) to examine whether hearing loss severity (as measured with CDTT) significantly predicted degree of improvement in stride time variability following training (Hypothesis 2) included the following fixed effects: CDTT x Training x Time, CDTT x Sex, Age, MoCA, Education, and Condition, and the following random intercepts: Subject nested within Testing Site.

Stride length. The selected mixed effect model (conditional $R^2 = 0.86$, marginal $R^2 = 0.28$) to examine whether hearing loss severity (as measured with HHIE) significantly predicted degree of improvement in stride length following training (Hypothesis 2) included the following fixed effects: HHIE x Training x Time, HHIE x Sex, Age, MoCA, Education, and Condition, and the following random intercepts: Subject nested within Testing Site. The selected mixed effect model (conditional $R^2 = 0.87$, marginal $R^2 = 0.24$) to examine whether hearing loss severity (as measured with CDTT) significantly predicted degree of improvement in stride length following training (Hypothesis 2) included the following fixed effects: CDTT x Training x Time, CDTT x Condition, Sex, Age, MoCA, and Education, and the following random intercepts: Subject nested within Testing Site.

Stride length variability. The selected mixed effect model (conditional $R^2 = 0.27$, marginal $R^2 = 0.16$) to examine whether hearing loss severity (as measured with HHIE) significantly predicted degree of improvement in stride length variability following training

(Hypothesis 2) included the following fixed effects: HHIE x Training x Time, HHIE x Sex, HHIE x Age, MoCA x Age, Education, and Condition, and the following random intercepts: Subject nested within Testing Site. The selected mixed effect model (conditional $R^2 = 0.21$, marginal $R^2 = 0.16$) to examine whether hearing loss severity (as measured with CDTT) significantly predicted degree of improvement in stride length variability following training (Hypothesis 2) included the following fixed effects: CDTT x Training x Time, CDTT x Education, MoCA x Age, Sex, and Education, and the following random intercepts: Subject nested within Testing Site.

Double support time. The selected mixed effect model (conditional $R^2 = 0.75$, marginal $R^2 = 0.27$) to examine whether hearing loss severity (as measured with HHIE) significantly predicted degree of improvement in double support time following training (Hypothesis 2) included the following fixed effects: HHIE x Training x Time, HHIE x Education, HHIE x Sex, MoCA x Age, and Condition, and the following random intercepts: Subject nested within Testing Site. The selected mixed effect model (conditional $R^2 = 0.74$, marginal $R^2 = 0.30$) to examine whether hearing loss severity (as measured with CDTT) significantly predicted degree of improvement in double support time following training (Hypothesis 2) included the following fixed effects: CDTT x Training x Time, CDTT x MoCA, Age, Sex, Education, and Condition, and the following random intercepts: Subject nested within Testing Site.

Results

Effect of Hearing Loss on Single- and Dual-Task Performance at Baseline

To address our first research question of whether dual-task performance differed across MCI participants with normal hearing or hearing loss at baseline, we first examined whether there were any differences in participant characteristics across hearing groups (Supplementary Table 1). Hearing groups were not significantly different with regards to age, MoCA scores, or the proportion of males and females. However, participants with hearing loss had significantly fewer years of education compared to those with normal hearing. Years of education was therefore included as a covariate in all further analyses. HHIE-S scores were also significantly higher in participants with hearing loss compared to normal hearing, indicating a higher degree of perceived impediment due to hearing loss.

Supplementary Table 1

Means, Standard Deviations, and One-Way ANOVAs/Chi Square Tests for Participant Characteristics and Background Measures Across Hearing Groups at Baseline

	Normal Hearing $n = 56$		Hearing Loss $n = 19$		*F or* χ^2	*p*	η_p^2
	M	*SD*	*M*	*SD*			
Age (years)	72.86	7.06	76.00	5.23	3.15	.080	.041
Sex (*n*, % female)	24 (42.86)		8 (42.11)		.003	.954	
Education (years)	16.24	4.22	14.16	2.50	4.11*	.046	.053
MoCA (/30)	23.34	2.89	21.89	3.04	3.45	.067	.045
HHIE-S (/40)	5.20	6.34	17.47	9.45	40.53**	<.001	.498
CDTT SRT (SNR)	-10.36	1.30	-4.23	5.14	49.04	<.001	.490

Note. MoCA = Montreal Cognitive Assessment; HHIE-S = Hearing Handicap Inventory For The Elderly - Screening Version; CDTT SRT = Canadian Digit Triplet Test – Speech Response Threshold; SNR = Signal to noise ratio; Hearing loss was characterized by an abbreviated pure-tone audiometry assessment, wherein participants who were unable to detect a 2-kHz tone at 25 dB HL in both ears were classified as being hearing impaired; * $p < .05$, ** $p < .001$

In examining single- and dual-task gait performance across hearing groups at baseline (Research Question 1), we found a significant main effect of Task for stride time, *F* (1, 211) = 21.84, *p* < .001, η_p^2 = .09, stride time variability, *F* (1, 211) = 5.39, *p* = .02, η_p^2 = .02, stride length, *F* (1, 211) = 5.22, *p* = .02, η_p^2 = .02, stride length variability, *F* (1, 211) = 7.64, *p* = .006, η_p^2 = .03, and double support time, *F* (1, 211) = 18.49, *p* < .001, η_p^2 = .08, such that performance was worse under dual-task conditions compared to the single-task condition (Supplementary Table 2). We found marginally significant Hearing Ability by Task interaction effects for stride time variability, *F*(1, 211) = 3.55, *p* = .06, η_p^2 = .02, and stride length variability, *F*(1, 211) = 2.77, *p* = .097, η_p^2 = .01, such that dual-task performance was significantly worse compared to single-task performance in participants with hearing loss, but not in participants with normal hearing (Supplementary Table 2).

To better understand the marginally significant Hearing Ability by Task interaction effects for stride time variability and stride length variability, we examined the relative performance across single- and dual-task domains (i.e., dual-task costs [DTC]: single-task – dual-task/single-task*100) between hearing groups. We found a significant main effect of Hearing Ability for stride time variability DTCs, *F* (1, 154) = 5.64, I = .019, η_p^2 = .04, such that participants with hearing loss had higher DTCs (*M* = 35.4%, *SE* = 10.53), compared to participants with normal hearing (*M* = 15.0%, *SE* = 6.13).

Marginally significant Hearing Ability by Condition interactions were also found for stride time variability, *F*(3, 207) = 2.13, *p* = .098, η_p^2 = .03, and stride length variability, *F*(3, 207) = 2.31, *p* = .078, η_p^2 = .03. Post hoc analyses revealed that in participants with normal hearing, stride time variability was significantly higher when walking was paired with S7 subtractions (*M* = 3.17%, SE = .18) compared to S1 subtractions (*M* = 2.39%, *SE* = .18, *p* =

.002). There were no significant differences in stride time variability across conditions in participants with hearing loss. Post hoc comparisons for stride length variability revealed that in participants with hearing loss, stride length variability was significantly higher in the semantic fluency condition (*M* = 4.27%, *SE* = .35) compared to the S1 subtraction condition (*M* = 3.04%, *SE* = .35, *p* = .02). There were no significant differences in stride length variability across conditions in participants with normal hearing. Finally, within the semantic fluency condition, stride length variability was found to be marginally higher in participants with hearing loss compared to normal hearing (*M* = 3.47%, *SE* = .21, *p* = .05).

In contrast to our hypotheses, we did not find any significant differences in cognitive accuracy across participants with normal hearing and hearing loss at baseline. We also did not find any significant differences across single-task and dual-task cognitive performance at baseline (Supplementary Table 2).

Supplementary Table 2

Single- and Dual-Task Gait and Cognitive Performance across Hearing Groups at Baseline

	Normal Hearing (*n* = 56)		Hearing Loss (*n* = 19)		Total (*n* = 75)	
	ST	DT	ST	DT	ST	DT
Stride length (cm)	132 (2.40)	128 (2.27)***	126 (4.34)	131 (4.54)*	131 (2.52)	127 (2.43)***
Stride length variability (%)	3.07 (.21)	3.35 (.15)	2.66 (.35)	3.60 (.25)**	2.86 (.20)	3.48 (.14)**
Stride time (ms)	1091 (17.4)	1166 (16.1)***	1072 (29.7)	1145 (27.6)***	1081 (16.5)	1156 (15.5)***
Stride time variability (%)	2.75 (.18)	2.78 (.13)	2.30 (.30)	2.98 (.21)*	2.52 (.17)	2.88 (.12)*
Double support time (ms)	323 (9.38)	348 (8.48)***	313 (16.00)	353 (14.57)***	318 (9.07)	350 (8.20)***
Cognitive accuracy (correct/time)	.49 (.03)	.56 (.03)	.57 (.06)	.61 (.06)	.53 (.03)	.58 (.03)

Note. ST = single-task; DT = dual-task; Hearing loss was characterized by an abbreviated pure-tone audiometry assessment, wherein participants who were unable to detect a 2-kHz tone at 25 dB HL in both ears were classified as being hearing impaired; Dual-task gait performance was aggregated across the serial 1 subtractions, serial 7 subtractions, and semantic fluency conditions; Cognitive performance was aggregated across the serial 7 subtraction and semantic fluency tasks for both the single- and dual-task conditions; Asterisks indicate significant differences between single-task and dual-task; *** $p < .001$; ** $p < .01$; * $p < .05$.

Effect of Hearing Loss on the Change in Single- and Dual-Task Performance from Pre- to Post-Training

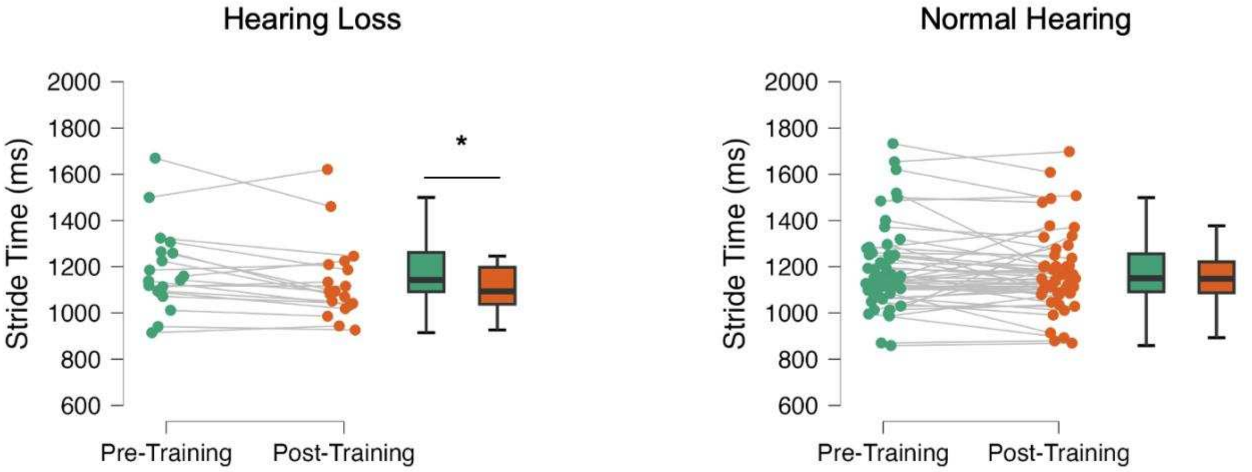
In examining whether hearing ability moderated single- and dual-task performance from pre- to post-training (Research Question 2), we found significant Time by Hearing Group interaction effects for dual-task stride time, $F(2, 345) = 7.21$, $p = .008$, $F\ (2, 346) = 7.20$, $p = .007$, $\eta_p^2 = .02$, stride time variability, $F\ (2, 349) = 6.15$, $p = .01$, $\eta_p^2 = .02$, and double support time, $F\ (1, 346) = 5.64$, $p = .02$, $\eta_p^2 = .02$. Specifically, dual-task stride time (Δ = - 50.82 ms, $SE = 12.66$, $p < .001$), stride time variability (Δ = .60%, $SE = .23$, $p = .01$), and double support time (Δ = - 27.49 ms, $SE = 7.62$, $p < .001$) significantly improved in participants with hearing loss, but not in participants with normal hearing, regardless of training modality (Supplementary Figures 1-3). There was also a significant Time by Training Group by Hearing Group interaction for dual-task stride length, $F\ (2, 347) = 3.86$, $p = .02$, $\eta_p^2 = .02$. Post hoc pairwise analyses revealed that following Ex + CT, dual-task stride length significantly improved in participants with hearing loss (Δ = 7.53 cm, $SE = 2.00$, $p < .001$), and marginally improved in participants with normal hearing (Δ = 2.52 cm, $SE = 1.28$, $p = .05$).

There was no effect of hearing loss on single-task gait performance following training. We further examined DTC scores for the reported interactions to elucidate whether individual differences in single-task gait measures affected the observed patterns. We found a significant Time by Hearing Ability interaction for stride time DTCs, $F\ (1, 348) = 5.60$, $p = .02$, $\eta_p^2 = .02$, such that DTCs significantly decreased (i.e., improved) in participants with hearing loss (Δ = -1.82%, $SE = .89$, $p = .04$), but not in participants with normal hearing (Δ = 0.34%, $SE = 0.55$, $p = .53$). There was a marginally significant time by Hearing Ability interaction for stride time variability DTCs $F\ (1, 350) = 3.77$, $p = .05$, $\eta_p^2 = .01$, such that DTCs significantly decreased in hearing loss participants only (Δ = -29.2%, *SE* = 11.02, *p* = .01). Finally, we found a significant Time by Hearing Ability by Training Group interaction for double support time DTCs, *F* (2, 350) = 4.00, *p* = .02, η_p^2 = .02, such that following the BAT + sham CT training, double support time DTCs significantly increased (i.e., worsened) in normal hearing participants (Δ = 7.07%, *SE* = 3.00, *p* = .01), whereas DTCs significantly decreased in participants with hearing loss (Δ = -9.96%, *SE* = 4.87, *p* = .04).

Regarding cognitive accuracy, there were no significant changes in both single- and dual-task performance following training, nor were there any significant differences found across hearing groups (see Supplementary Table 3 for estimated marginal means of dual-task gait and cognitive performance before and after training across hearing groups and intervention arms).

Supplementary Figure 1

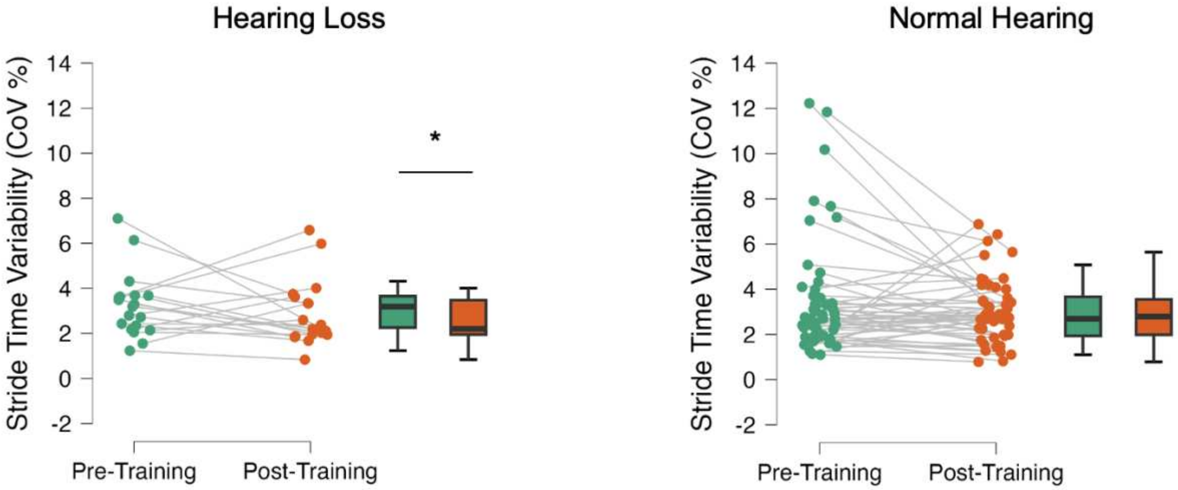
Dual-Task Stride Time Before and After Training Across Participants with Hearing Loss and Normal Hearing



Note. Hearing loss was characterized by an abbreviated pure-tone audiometry assessment, wherein participants who were unable to detect a 2-kHz tone at 25 dB HL in both ears were classified as being hearing impaired; Each circle represents a participant, with the connecting line depicting the individual change scores from pre- to post-training; Dual-task performance was aggregated across the serial 1 subtractions, serial 7 subtractions, and semantic fluency conditions. Training was aggregated across the three intervention arms (i.e., aerobic-resistance exercise (Ex) with cognitive training (CT), Ex with sham CT, and balance and toning with sham CT); * $p < .01$.

Supplementary Figure 2

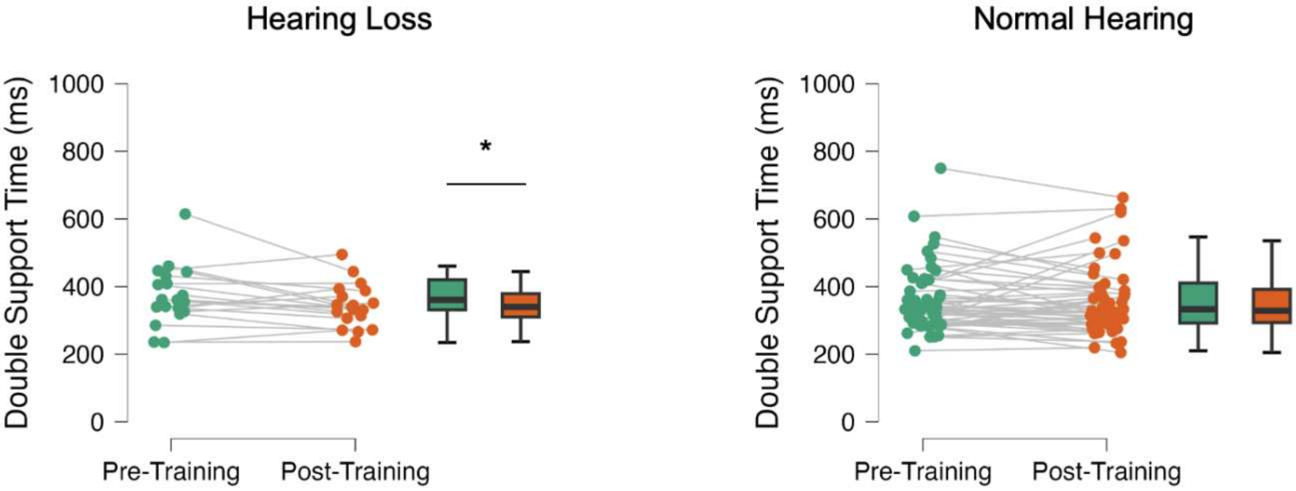
Dual-Task Stride Time Variability Before and After Training Across Participants with Hearing Loss and Normal Hearing



Note. Hearing loss was characterized by an abbreviated pure-tone audiometry assessment, wherein participants who were unable to detect a 2-kHz tone at 25 dB HL in both ears were classified as being hearing impaired; Each circle represents a participant, with the connecting line depicting the individual change scores from pre- to post-training; Dual-task performance was aggregated across the serial 1 subtractions, serial 7 subtractions, and semantic fluency conditions. Training was aggregated across the three intervention arms (i.e., aerobic-resistance exercise (Ex) with cognitive training (CT), Ex with sham CT, and balance and toning with sham CT); * $p < .05$.

Supplementary Figure 3

Dual-Task Double Support Time Before and After Training Across Participants with Hearing Loss and Normal Hearing



Note. Hearing loss was characterized by an abbreviated pure-tone audiometry assessment, wherein participants who were unable to detect a 2-kHz tone at 25 dB HL in both ears were classified as being hearing impaired; Each circle represents a participant, with the connecting line depicting the individual change scores from pre- to post-training; Dual-task performance was aggregated across the serial 1 subtractions, serial 7 subtractions, and semantic fluency conditions. Training was aggregated across the three intervention arms (i.e., aerobic-resistance exercise (Ex) with cognitive training (CT), Ex with sham CT, and balance and toning with sham CT); * $p < .05$.

Supplementary Table 3

Estimated Marginal Means and Standard Errors of Dual-Task Performance Before and After Training Across Hearing Groups and Intervention Arms

Measure	Ex + CT *n* = 32				Ex + sham CT *n* = 31				BAT + sham CT *n* = 12			
	Normal Hearing n = 23		Hearing Loss *n* = 9		Normal Hearing *n* = 24		Hearing Loss *n* = 7		Normal Hearing *n* = 9		Hearing Loss *n* = 3	
	T1	T2	T1	T2	T1	T2	T1	T2	T1	T2	T1	T2
Gait speed (cm/s)	112 (4.74)	119 (4.74)*	118 (6.62)	124 (6.62)*	107 (4.72)	112 (4.71)*	113 (8.07)	117 (8.07)*	108 (7.52)	108 (7.47)	113 (9.03)	113 (9.00)
Stride time (ms)	1160 (26.9)	1134 (26.9)*	1126 (40.4)	1078 (40.4)*	1174 (25.8)	1171 (25.8)	1154 (50.5)	1117 (50.5)*	1140 (44.0)	1163 (43.6)	1209 (70.2)	1142 (70.2)*
Stride time variability (CoV%)	2.74 (.22)	2.50 (.22)	3.11 (.33)	2.51 (.33)*	2.79 (.21)	2.95 (.21)	2.61 (.41)	2.59 (.41)	2.84 (.37)	3.19 (.35)	3.49 (.57)	2.33 (.57)*
Stride length (cm)	129 (3.75)	132 (3.74)	123 (5.62)	130 (5.62)*	123 (3.57)	126 (3.57)*	121 (7.76)	119 (7.76)	127 (6.09)	128 (6.05)	123 (9.81)	123 (9.81)
Stride length variability (CoV%)	3.24 (.25)	3.05 (.24)	4.00 (.37)	3.56 (.37)	3.56 (.24)	3.63 (.24)	3.12 (.45)	3.15 (.45)	3.29 (.43)	3.85 (.40)	3.56 (.64)	3.13 (.64)
Double support time (ms)	341 (13.7)	327 (13.6)*	331 (20.5)	311 (20.5)*	356 (13.1)	353 (13.1)	356 (25.6)	337 (25.6)	345 (22.9)	352 (22.6)	393 (35.5)	352 (35.5)*
Double support time variability (CoV)	7.37 (.51)	5.65 (.50)*	6.16 (.76)	5.02 (.76)	6.38 (.49)	6.49 (.49)	5.36 (1.02)	5.82 (1.02)	6.74 (.84)	6.91 (.82)	6.50 (1.33)	4.71 (1.33)
Cognitive accuracy (number correct/ time)	.79 (.04)	.85 (.04)	.85 (.07)	.81 (.07)	.75 (.04)	.83 (.04)	.86 (.12)	.75 (.12)	.69 (.07)	.73 (.69)	.93 (.12)	.98 (.12)

Note. T1 = Time 1 (baseline); T2 = Time 2 (post-training); Standard error in brackets; Hearing loss was characterized by an abbreviated pure-tone audiometry assessment, wherein participants who were unable to detect a 2-kHz tone at 25 dB HL in both ears were classified as being hearing impaired; Performance in each domain is the aggregated score across the serial 1 subtractions, serial 7 subtractions, and semantic fluency conditions; cognitive accuracy scores were calculated by dividing the total number of correct items divided by the time to complete the walking trial; * $p < .05$ between pre- and post-training.