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A novel dual-task paradigm for evaluating the interplay between gait, cognition, and hearing loss in normal aging and MCI: Effects of Dichotic Listening during overground walking

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A dissertation for the degree of Philosophiae Doctor, January 2022

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Acknowledgements

I started my PhD journey in 2013 as a PhD candidate in the Project Double Competence. This project was carried out at the UiT - The Arctic University of Norway. Nine years have passed, the final product is now done, and what a ride it has been! Throughout these years, I am so fortunate and grateful to have received so much support from so many.

My sincerest gratitude goes to my main supervisor, professor Claudia Rodríguez-Aranda. Thank you for believing in me, for all the scientific and emotional support, for the enthusiasm and dedication, for your patience, guidance, wisdom, and knowledge. I am immensely grateful for our collaboration that started back in 2009.

I would also like to thank my co-supervisor Knut Waterloo, for the extensive knowledge, and for introducing me to the exciting field of clinical neuropsychology. A great thanks goes to my research group, its current and previous members, for all the laughs, insights, and collaborations. I wish to thank all our lab assistants contributing to our umbrella project for their valuable time and assistance.

I wish to thank the staff at the Department of Geriatrics and the Department of Neurology at the University Hospital of North-Norway for all support with data acquisition. Most importantly, I wish to thank all the wonderful participants in our project. This would not have been possible without you.

To my dear colleagues at the Department of Psychology - you rock! A special thanks to senior engineer Thomas Nermo for technical and emotional support throughout all these years. To my inspiring former office mate, Marte Rye, I miss you! Sincere thanks to the team of clinical neuropsychology: Jørgen Sundby, Karen Hopmann, and Ingvild N. Myrbakk, for all the patience and flexibility to help me finish this doctoral work.

Many special thanks go to my family: my mom Sylwia, Simon, my brother Alex. To my late dad, Steinar. Serdeczne podziękowania kochanej rodzinie w Polsce <3. Deep and loving thanks to my partner, Chris. I thank you all for your never-ending encouragement and support, for all the love, and for helping me through all trials and tribulations. You are the best.

Great thanks go to my own cheer team: To my rock, Gry. To my squad: Andrea, Haldis, Henriette, and Maria. To Magnus, my Ninja. To Henrik, for always saying yes. To the Perez Pack for always having my back. So many years of your support and encouragement have kept me going on, guys.

The list of thank you could have gone on forever, and there would not be enough space on this page to mention everyone. There are a lot of you but know this: I cherish and thank each one of you, from the bottom of my heart.

List of papers

This thesis is based on the following papers, which are referred to in the text as Paper I, Paper II and Paper III.

Paper I

Gorecka, M.M., Vasylenko, O., Espenes, J., Waterloo, K., & Rodríguez-Aranda, C. (2018). The impact of age-related hearing loss and lateralized auditory attention on spatiotemporal parameters of gait during dual-tasking among community dwelling older adults. *Experimental Gerontology,* 111, 253-262. https://doi.org/10.1016/j.exger.2018.07.015

Paper II

Gorecka, M. M., Vasylenko, O., & Rodríguez-Aranda, C. (2020). Dichotic listening while walking: A dual-task paradigm examining gait asymmetries in healthy older and younger adults. *Journal of Clinical and Experimental Neuropsychology,* 42 (8), 794-810. https://doi.org/10.1016/j.exger.2018.07.015

Paper III

Gorecka, M.M., Vasylenko, O., Waterloo, K. & Rodríguez-Aranda, C. (2021). Assessing a sensory-motor-cognition triad in amnestic Mild Cognitive Impairment with dichotic listening while walking: A dual-task paradigm. *Frontiers in Aging Neuroscience*, *13*(757), https://doi.org/10.3389/fnagi.2021.718900

Abbreviations

EF - Executive Functions

MCI – Mild Cognitive Impairment

aMCI – amnestic Mild Cognitive Impairment

naMCI – non-amnestic Mild Cognitive Impairment

AD – Alzheimer's Disease

DL – Dichotic Listening

CV – Consonant-Vowel

REA – Right Ear Advantage

LEA – Left Ear Advantage

CoV – Coefficient of Variation

DTC – Dual Task Cost

NF – Non-Forced

FR – Forced Right

FL – Forced Left

AHRL – Age-Related Hearing Loss

CAPD – Central Auditory Processing Disorder

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Abstract

Background and aims. Much research has been conducted on the association between gait and cognition regarding cognitive decline and risk of falls. The go-to method to study this relationship is the dual-task paradigm, however a better understanding of the mechanisms behind this interplay is needed. Previous dual-task research has lacked consistency in methods in terms of choice of cognitive task and walking procedure, and thus, complicated transferability of results. To study the interrelated triad between attention impairments, hearing loss, and gait perturbations in aging, we introduced a novel dual-task paradigm including a Dichotic Listening (DL) task. DL has different attentional demands, which are performed concomitantly with overground walking. This approach may be considered to be more ecological valid than previous approaches as it mimics a listening and talking while walking – situation. The overall aims of this doctoral thesis were to evaluate the effects of how lateralized verbal attention required by DL affects walking in healthy young adults, healthy older adults, and in individuals with amnestic Mild Cognitive Impairment (aMCI). Hearing loss has shown to influence both balance and cognition, and in this thesis the moderating influence of hearing loss on dual-task performance was also investigated.

Methods. Participants were healthy older adults (Paper I, Paper II, Paper III), younger adults (Paper II) and older adults with aMCI (Paper III). All participants were interviewed about background and health status. The cognitive abilities were assessed by a comprehensive neuropsychological battery, and hearing status was evaluated by audiometric screening. Afterwards, participants conducted a novel dual-task approach involving the Bergen Dichotic Listening Task concomitantly with walking overground. The DL task consisted of three attentional conditions where participants reported spontaneously the clearest syllable (*Non-Forced*), and two volitional conditions, directing attention to either right or left ear (*Forced Right* and *Forced Left*, respectively). Gait parameters were acquired by a novel motion analysis system: the OptoGait. Mean and variability values were obtained for different spatiotemporal gait parameters: Step length, stride length, step width, and gait speed. In addition, these were analyzed bilaterally, i.e., both limbs together, and laterally, i.e., limbs analyzed separately. In Paper II, dual task costs, and percentage change from Baseline (i.e., percent of Baseline) were calculated.

Statistical analyses. Factorial analyses of variance and covariance were used to assess group differences and the moderating role of hearing-status. Pearson correlations were used in Paper I and t-test analyses were applied for group comparisons of cognitive data.

Results and Discussion. Performing DL while walking overground caused an increment in gait variability and the appearance of asymmetries in most of the study groups. Unexpectedly, this was

seen to a larger extent in the healthy groups and after controlling for hearing acuity. The Non-Forced condition evoked gait asymmetries and higher variability in step length and gait speed. The directed attention conditions caused an even higher increment in variability in stride length and step length, as well as asymmetries, in the healthy study groups. Focusing attention to the right side did increment gait variability in healthy older adults who still managed to report correctly from the right side. In contrast, attending the left side caused more variability in all study groups, especially in healthy older adults who indeed attended left-ear stimuli. In contrast, the aMCI group did not show lateralized gait effects due to a lack of ability to perform the DL test.

Regarding the DL results, older adults showed a Right Ear Advantage across all DL-conditions in all papers and showed more difficulties in reporting from the left-side. Younger adults on the other hand displayed the ability to focus attention as instructed. In the aMCI-group, no difference in listening preference was seen across the DL-conditions indicating lack of ear advantage.

The present work shows that lateralized attention control depends on hearing acuity and affects gait differently in various healthy populations and groups prone to develop dementia. This work advances the current understanding of the involvement of attention and executive function in gait and the importance of sensory loss. Results are relevant in fall detection assessment and rehabilitation interventions in both research and clinical contexts.

1 Introduction

Aging entails many alterations in cognition, motor, and sensory functions linked to functional decline and loss of adaptability. Consequently, gait and mobility disorders increase with advancing age and lead to an increase in risk of falls. A fall is defined as *"unintentional coming to the floor, ground or other lower surface not due to seizure or stroke*" and falling is a common geriatric syndrome affecting 1/3 of older adults annually (Tinetti et al., 1988). According to the World Health Organization, approximately 28-35 percent of adults above 65 years of age experience fall each year, and the frequency of falls increase with age and frailty level. Falls account for a substantial injury and are considered a major public health problem in terms of morbidity, hospital duration, and mortality (Li et al., 2006; Sudarsky, 2001; Tinetti et al., 1988). Approximately 40 million falls with enough severity to require medical attention occur each year and increasing age is the largest risk factor for falls (World Health Organization, 2008). Thus, falls are a global problem due to the increased rates of the costs associated with treating impairments. In Norway, approximately 9000 hip fractures occur per year due to falls (Omsland et al., 2012). The health consequences of falls in the elderly are substantial, not mentioning caregiver burden, and indirect costs of healthcare systems.

Between 2015 and 2050, the proportion of the world's population over 60 years will nearly double from 12% to 22% (World Health Organization, 2015). Considering the increasing global aging population, more attention towards identification of fall risk and fall prevention is needed.

It is well established that a substantial number of falls occur during walking, the most common daily living activity in humans (Maki, 1997; Sartini et al., 2009). However, the causes of falls are poorly understood. Falls are multifactorial, consisting of both extrinsic and intrinsic risk factors. Extrinsic risk factors include environmental risks such as tripping hazards (e.g., throw rugs on floors), footwear, lack of stair railings, and poor lighting conditions, any of which can cause falls. Intrinsic risk factors generally include personal characteristics such as age, gender, physiological impairments, and medication use, among others, that can predispose an individual to falling (Rosen et al., 2013; Tinetti et al., 1988). The recent decades of research on falls have changed focus from falls being accidental or extrinsic to more focus on pathological conditions in falling individuals. Nevertheless, it is important to consider falls as a dynamic interaction of intrinsic and extrinsic factors as successful walking requires an integration of several aspects of the environment in addition to cognitive resources, mobility, sensory and perceptual abilities (Montero-Odasso & Camicioli, 2020). Until recently, cognitive impairment, dementia, and falls have been assessed separately, leading to a gap in the understanding of how the relationship between cognition and motor abilities affect falls. This gap also explains why cognition have received little attention in fall prevention strategies. Furthermore, the critical role of cognition in risk of falls has previously received little attention in the medical literature (Montero-Odasso & Camicioli, 2020). Although there are many causes of mobility deteriorations and declines in older age, these generally depend on underlying age-related structural and functional changes in the brain, and an increasing body of research is emerging on how gait and cognitive impairments are interrelated and associated with aging (Montero-Odasso, Verghese, et al., 2012).

Therefore, the present thesis was motivated to help filling this gap by applying a novel and ecological method for a better understanding of the association between cognition and walking in older adults. The use of a dual-task paradigm involving dichotic listening (DL) with walking overground is the central topic of this investigation. In parallel, this thesis also highlights the importance of a specific sensory loss relevant for the mentioned paradigm, influencing the cognitive-motor dyad, namely hearing loss. In order to provide a solid background for this investigation, I will address relevant issues and research related to the cognition-gait association in the aging spectrum, dichotic listening, and the role of age-related hearing loss. Thereafter, the aims and interest of the present thesis will be presented, together with an account of the conducted studies conforming this doctoral work.

2 Age-related changes in gait in normal aging

Walking is a fundamental part of mobility and thus, a key aspect of independence in daily life. Generally speaking, gait and walking are words used interchangeably as synonyms about the same action, bipedal ambulation. However, gait describes the detailed pattern of movements during locomotion (Levine, 2012).That said, in this thesis the walking pattern is the focus of study. The gait cycle is described as the distance covered by two heel strikes of the same foot, consisting of a swing phase and support phase (Payne & Isaacs, 2017), and normal gait is characterized by a cyclic pattern of spatial and temporal characteristics (Hollman et al., 2011). With increasing age, gait changes and disturbances arise, which affect quality of life negatively (Jahn et al., 2010; Montero-Odasso, Verghese, et al., 2012; Verghese et al., 2009). Gait disturbances in old age are related to sensory deficits (like visual impairment), age-related decline in muscle mass, skeletal changes, neurodegenerative disease (Parkinsonism, ataxia, dementia), vascular encephalopathy, normal pressure hydrocephalus, anxiety, and cognitive decline. Some gait perturbations also appear in disease-free individuals, for instance after injury (Rose & Gamble, 2005).

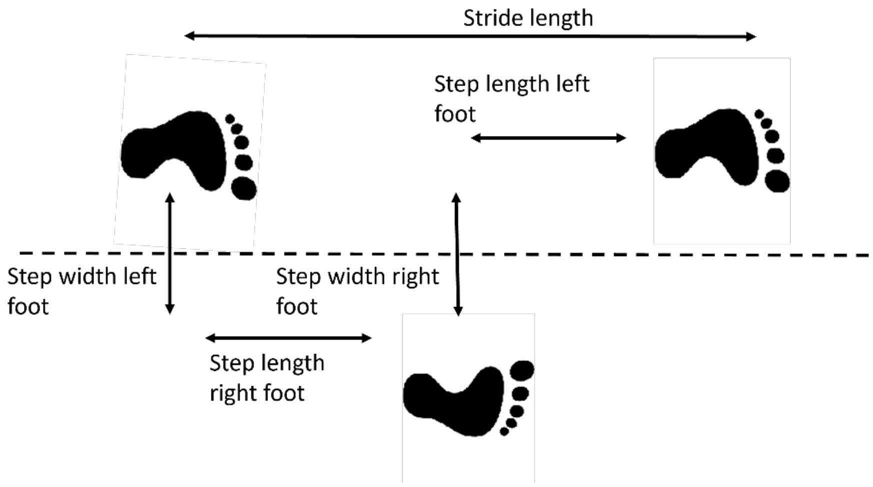
2.1. What characterizes gait in older adults?

Gait is dynamic and fluctuates with time, and changes from one stride to the next, even when environmental conditions are fixed (Hausdorff, 2005). In aging, some fundamental gait changes occur, being the most evident the decrease in gait velocity and step length, as well as increment in the time that both feet are on the ground simultaneously (i.e., double support stance phase) and wider step width. This age-related walking pattern is considered as cautious, or conservative gait, that promotes individuals to preserve their posture and balance (Herssens et al., 2018; Nutt, 2001).

In the following section, a selection of typical spatial and temporal measures associated with adverse health outcomes in aging are described. Figure 1 illustrates spatial parameters in the gait cycle

Figure 1.

An illustration of spatial parameters in the gait cycle



Gait speed. The earliest change seen in gait among older adults is slowing of speed. Also, cognitively impaired persons show more slowing of gait speed compared to healthy older adults (Fasano et al., 2012). Gait speed is the most profound indicator of gait dysfunction in older adults and has become a screening parameter for multiple geriatric syndromes (Abellan van Kan et al., 2009). In addition, gait speed has been proposed to be a screening criterion for cognitive decline in both the recent Motor Cognitive Risk Syndrome and mild cognitive impairment (MCI) (MacAulay et al., 2017; Verghese et al., 2013).

Step length. The length from the heel of the previous footfall to the heel of the current opposing footfall decreases in aging (Kirkwood et al., 2011; Laufer, 2005), and has shown to be associated with falls (Callisaya et al., 2012).

S***tride length.*** The distance between the posterior heel points of two consecutive footprints of the foot in question, gets shorter with aging and is associated with adverse health effects, physical disability, and mortality (Bytyçi & Henein, 2021).

Step width. The distance measured between line of progression of the left foot and the line of progression of the right foot is shown to increase with aging (Aboutorabi et al., 2016).

Gait variability. A quantifiable feature of fluctuation in time and distance from one footfall to the other is referred to as step-to-step variability and is useful for assessing motor control mechanisms. Spatial and temporal variability is altered (both in terms of magnitude and dynamics) in clinically relevant syndromes, such as falling, frailty, and neurodegenerative disease. This measure can only be accurately measured with special equipment to record the distance and duration between each footfall (Pieruccini-Faria et al., 2020). In clinical research, variability is calculated and evaluated in the means of coefficient of variation (CoV), which is calculated as follows and expressed in percentage (Hausdorff, 2005; Moon et al., 2016):

$$CoV\ (\%) = \left(\frac{Standard\ deviation}{Mean}\right) \times 100$$

Low variability is an estimate of an individual’s motor proficiency or the automaticity, i.e., the amount of conscious attention dedicated to the performance of a motor task (Dhawale et al., 2017). High gait variability represents gait instability, and it has been shown to predict falls, even before gait slows down in older adults (Callisaya et al., 2009; Hausdorff, 2005; Hausdorff et al., 2001).

Both temporal and spatial gait variability increases with aging but are also associated with functional decline and comorbidities (Moon et al., 2016; Rodríguez-Molinero et al., 2019; Verghese et al., 2002). Various studies have demonstrated variability in different gait parameters, (e.g., stride, step length, step width) to be associated with early risk of falls. Therefore, gait variability has emerged as sensitive marker of higher cognitive control (Al-Yahya et al., 2011; Hausdorff, 2005; Martin et al., 2012).

Age influences gait performance and stability, and gait measures also differ across various groups in older adults (Aboutorabi et al., 2016; Herssens et al., 2018; Hollman et al., 2011). However, some researchers also propose that some gait characteristics are relatively stable in older adults, like step width (Herssens et al., 2018). Interestingly, these changes are also considered as stabilizing mechanisms in walking and thus, compensatory. As a side note but also important, fear influences gait in old age (Ayoubi et al., 2015; Makino et al., 2017), and it has been suggested that the aforementioned gait changes in aging are actually stabilizing fear-related adaptations, rather than risk factors that increase the likelihood of falling (Maki, 1997).

To summarize, gait gets slower, step and stride length get shorter and also more variable with aging. These aspects cause older adults to adopt a more conservative gait pattern, compared to younger adults. In addition, walking on uncertain and irregular surfaces increases these gait characteristics (Ippersiel et al., 2021).

2.2 Gait and dementia

Traditionally, walking has been considered to be an automated, over-learned process. However, in the last decades this simplistic view has been challenged, showing that even routine walking has more in common with complex motor tasks demanding higher cognitive functions, especially in older adults. This notion has attracted more research interest in the role of cognition in gait changes associated with cognitive impairment. In aging, cognitive impairment is categorized on a spectrum of cognitive decline, from normal aging transitioning to intermediate states like Mild Cognitive Impairment (MCI) and further reaching the endpoint of dementia. Dementia has been considered a predominantly cognitive disorder; however, increasing evidence have been reported showing gait abnormalities in early stages of the disease (Beauchet et al., 2016; Verghese et al., 2008). Moreover, gait disorders increase with dementia severity, and falls are highly prevalent in individuals with cognitive decline. Older adults with dementia are 2-3 times more likely to experience falls than non-demented older adults (Allali et al., 2016; Eriksson et al., 2009; Fernando et al., 2017; Härlein et al., 2009). Slowing of gait has been considered the dominant feature in dementia and studies have shown that slower walking capacity is associated with increased risk of incident dementia (Beauchet et al., 2016; Buracchio et al., 2010; Montero-Odasso et al., 2020). Lower levels of cognitive functioning are shown to be risk factors for the development of motor impairment (Hausdorff & Buchman, 2013; Mirelman et al., 2012; Soumaré et al., 2009). These associations suggest that decline in cognitive function and gait, as seen in dementia, may share neurobiological substrates. Thus, identifying the cognitive mechanisms that influence gait in aging is of great importance, as quantitative gait dysfunction has been shown to predict risk of cognitive decline in non-demented individuals (Verghese et al., 2007).

2.3 Gait and mild cognitive impairment

Mild cognitive impairment (MCI) is an intermediate stage of cognitive impairment that is considered a transitional phase from cognitive changes in normal aging to those typically found in dementia (Petersen, 2004). Current criteria in this clinical entity include cognitive complaints by the individuals also observed by informants, objective cognitive impairment but no dementia present and preserved activities of daily living (Petersen et al., 2014). This clinical concept has further been subtyped into MCI of amnestic type (aMCI) if performance on neuropsychological tests of episodic memory is poor and of non-amnestic MCI (naMCI) in the case of poor performance on neuropsychological tests covering cognitive domains other than memory, such as executive functions, language, or visuospatial abilities. Amnestic MCI is considered to be more prevalent among MCI subtypes and is the subtype more probable to convert into Alzheimer's Dementia (AD). Furthermore, the impairment could be characterized into one cognitive domain (MCI single domain) or to multiple domains (MCI multiple domains). Thus, classification of MCI can be in one of the four possible clinical MCI subtypes: (1) aMCI single domain, (2) aMCI multiple domains, (3) naMCI single domain and (4) naMCI multiple domains (Fischer et al., 2007; Petersen, 2004; Winblad et al., 2004).

Identification of cognitive impairment and falls at an early stage has become an increasingly important challenge. Hence, the search for biomarkers of MCI, including motor markers, that may predict conversion to dementia, is an area of research that has exploded in the last decades. Individuals with MCI have higher prevalence of gait impairments compared to healthy older adults (Verghese et al., 2008) and subsequently, there exists now increasing knowledge reporting that gait abnormalities precede cognitive impairment (Cohen et al., 2016; Montero-Odasso et al., 2014).

Notwithstanding, the relationship between gait and cognition in MCI is insufficiently understood. Major gait changes associated with MCI appear to evolve over a period of time and the most frequently noted change is slowing of gait speed (Masse et al., 2021). Also, studies have shown that slowing in gait speed and other gait deteriorations precede and predict cognitive impairment (Buracchio et al., 2010; Camicioli et al., 1998; Kikkert et al., 2016).

Furthermore, gait outcomes in MCI differ both in normal walking (Verghese et al., 2008), and in dual-task walking compared to cognitively healthy individuals (Doi et al., 2014; Montero-Odasso et al., 2009). Interestingly, most gait changes are not easily detectable in single-task walking, while dual-task walking can reveal various anomalies (Bridenbaugh & Kressig, 2014). In MCI, gait deteriorations have shown to be more prominent during the simultaneous performance of cognitively demanding tasks and several spatiotemporal parameters are more affected as compared to healthy individuals, for instance increased stride time variability, shorter step and stride length, and slower gait speed (Bahureksa et al., 2017; Montero-Odasso, Verghese, et al., 2012; Savica et al., 2017).

For example, slower gait speed has been found to correlate with worse performance on several cognitive domains, such as attention, memory, visuospatial skills, and language (Savica et al., 2017) and individuals with aMCI have significantly decreased gait speed compared to naMCI (Montero-Odasso et al., 2014). In fact, quite recently it has been shown that slower gait speed together with cognitive complaints, characterizes the condition of Motor Cognitive Risk Syndrome, which refers to older adults at risk for developing dementia (Allali et al., 2016; Verghese et al., 2013).

In sum, identification of gait alterations and their progression over time is important for gaining a better understanding of clinical aspects of MCI. There still exists few studies focusing on MCI and gait analysis, which would be a new indirect way for the evaluation of cognitive status in MCI (Montero-Odasso, Verghese, et al., 2012; Verghese et al., 2008). This takes us to the next section where we have a closer look to the connection between gait and cognition and how to investigate this link.

3 The link between gait and cognition in aging: the use of dual-task paradigm

As mentioned, many gait parameters are affected by increasing age and for instance, decline in gait speed is commonly used as clinical measure of function in older adults. Measuring gait speed is easy to perform, inexpensive, and does not require specialist training or equipment (Abellan van Kan et al., 2009). Typically, the measurement of gait speed is carried out under single-task conditions, in other words by just walking at a defined pace. Although, this does not properly reflect reality as individuals often require performing different activities while walking. Also, since cumulated evidence point to a relationship between cognitive abilities and gait, it has been necessary to study the cognition-gait association by observing how cognitively demanding tasks affect gait. For instance, when humans attempt to perform more than one task at a time, performance on either task is reduced. The decline in gait performance is seen in particular when performing two tasks at the same time, especially for older adults (Woollacott & Shumway-Cook, 2002). Thus, the above situation is easily evoked by the dual-task paradigm, which simply entails observing people walking while they perform a secondary task. The dual-task paradigm has become the gold standard assessment to evaluate the interactions between cognition and gait (Al-Yahya et al., 2011; Beauchet & Montero-Odasso, 2020).

Since the seminal "Stops Walking When Talking" study by Lundin-Olsson and colleagues (Lundin-Olsson et al., 1997), which showed that introducing a secondary task while walking caused an inability to perform one of the tasks successfully, an increasing number of such paradigms have been utilized to investigate the involvement of cognitive dysfunction in older adults and the connection with motor functions. Dual-task experiments involving walking and simultaneously conducting a cognitively demanding task, have proved to alter gait in older adults and predict risk of falls (Bayot et al., 2020; Muir-Hunter & Wittwer, 2016). Furthermore, these approaches reveal deficits not apparent in single-task assessment, especially in individuals with cognitive impairment, who exhibit dual-task related changes in gait not observed in age-matched healthy controls (Bayot et al., 2020; Menant et al., 2014;

Muir-Hunter & Wittwer, 2016). In addition, older adults, compared to healthy young adults, show more perturbations in gait when the cognitive task complexity increases (Al-Yahya et al., 2011).

3.1 Types of dual-task paradigms employed in the study of gait and cognition

Various dual-task paradigms have been employed and they vary in terms of concomitant cognitive task, walking protocol, and acquisition of gait measures. Also, differences exist in the walking environment, such as overground versus treadmill or use of obstacles. For the purpose of this thesis, an overview about the type of cognitive task used in dual-task paradigms with older adults will be next presented, as well as background information concerning walking procedures and acquisition.

3.1.1 Cognitive tasks employed in dual-task experiments

In dual-task experiments, a plethora of cognitive tasks are applied as concomitant tasks. The most common are those relying on mental tracking, characterized by holding information in short-term memory while performing a mental process and they provide insight into sustained attention and information processing speed capacities of an individual (Lezak et al., 2012). Examples are serial subtraction, counting backwards by ones/threes/sevens, verbal fluency, arithmetic tasks, trail making tests or Stroop tasks (Al-Yahya et al., 2011; Smith et al., 2017).

It has been suggested that mental tracking tasks induce greater gait changes compared to cognitive tasks of external interfering factors, e.g., reaction time tasks. Furthermore, mental tracking tasks differ in types of instructions and difficulty, and thus, some of them may not provide sufficient cognitive load or activation to detect cognitive difficulties in older adults (Al-Yahya et al., 2011; Beauchet et al., 2005; Pashler, 1994). For example, it is suggested that in some older populations, more automatized cognitive processes like counting backwards, may be preserved, for instance in individuals with MCI (Bishnoi & Hernandez, 2021; Hunter et al., 2018; Nascimbeni et al., 2015). In such a case, counting backwards by ones is easier to perform and will not disturb gait in persons with MCI during dual-tasking. The same type of tests, e.g., serial-threes and seven-subtractions, require more sustained attention and working memory which may cause more difficulties simultaneously while walking, possibly due to the difficulty level. In addition, serial subtractions have also demonstrated to be able to differentiate between healthy controls and MCI (Bishnoi & Hernandez, 2021; Montero-Odasso, Muir, et al., 2012).

Despite that mental tracking tasks have shown to affect gait the most in older adults, there are serious limitations with these tasks. They are either not specific to one cognitive function or most of them are too intricate so that findings cannot be generalized to everyday situations. Cognitive tasks in dual-task paradigms usually tap into different cognitive domains. However, they are not necessarily transferable to real –life activities. Many of these tasks are usually modifications of current neuropsychological tests involving verbal fluency, counting and auditory/visual interference (McFadyen et al., 2017). Furthermore, there is huge variation on the sensory modalities on which they rely on, as well as variation on cognitive load/difficulty and the majority are only applicable in laboratory settings.

For the above reasons, the application of varied cognitive tasks results in inconsistent findings. At this point, enough data have been collected to assert that mental tracking tasks affect the most gait parameters of older populations, but with the use of these tasks it has not been possible to conclude which exact cognitive operation is linked to a specific gait deterioration.

3.2 Walking procedures and measures employed in dual-task experiments

Many methods exist in the analysis and assessment of gait, for instance by self-report, visual inspection, or quantitative computer analysis. The use of subjective measures, (e.g., questionnaires or observations) is limited as such cannot provide detailed information about gait behavior, particularly because they cannot account for small and subtle movements during gait. No golden standard method exists, and gait analyses occur in various ways, e.g., video-based approaches, three-dimensional systems providing spatiotemporal variables, and systems assessing aspects of kinematics or kinetics. Though, the purpose of gait analyses is to diagnose and discover underlying pathologies and the extent of gait impairment, as well as developing rehabilitation programs (Bridenbaugh & Kressig, 2011; Muro-de-la-Herran et al., 2014).

One reliable and popular form of gait analysis is based on spatiotemporal measures, which provides measures without examiner bias (Muro-de-la-Herran et al., 2014). Some of the most used spatiotemporal parameters used to describe gait changes in aging are those presented in point 2 (see pages 14-15). As presented in that section, gait speed, step length, stride length and step width are widely reported in dual-task studies of older adults. Other parameters of interest in gait analysis are step time, cadence, double support time, stance, swing time, and single support time. Looking at gait from a spatial and temporal perspective allows us to measure gait asymmetries related to distance between steps and strides length (Roberts et al., 2017). It is though important to highlight that regardless of several attempts by authorities in the field, there is still a lack of consensus about which gait parameters are relevant to assess in aging, and for this reason, each study reports inconsistently different parameters across studies (Beauchet et al., 2017; Cullen et al., 2018; Hollman et al., 2011; Montero-Odasso et al., 2018). Nevertheless, spatiotemporal parameters are widely used and well-known gait measurements, and can be acquired in various situations, which will be described next.

3.2.1 Treadmills vs. overground walking

Depending on research interests, walking protocols vary and studies apply different types of walkways and solutions. For instance, treadmill walking has often been applied in experimental and clinical settings. However, application of dual-task paradigms on treadmills are not optimal. To begin with, this type of walking has been suggested by several studies not to be completely valid (Dingwell et al., 2017; McFadyen et al., 2017; Simoni et al., 2013; Wrightson et al., 2020) because it is imposed artificially.

It seems that treadmill walking for young healthy adults who perform a dual-task causes improvements on the cognitive task with no detrimental effects to gait, as compared to overground walking (Penati et al., 2020; Wrightson et al., 2020). Although, it has been assumed that treadmill findings transfer to overground walking, various research studies have demonstrated the opposite, indicating that involvement of control mechanisms are quite different from regular walking (Simoni et al., 2013; Wrightson et al., 2020; Wrightson & Smeeton, 2017). The use of treadmills is understandable, due to its practicality in clinical and experimental settings. However, it is undeniable that it poses challenges to older adults. By externally inducing pace, treadmills provide rhythmicity and automaticity and walking rely thus less on cognitive control, giving priority to the performance of the cognitive task. Treadmill walking may therefore prove more useful in a therapeutic rehabilitation setting, but not necessarily in the detection of subtle gait perturbations. For the above-mentioned reasons, overground walking is the desirable way to evaluate older populations. In overground walking, the allocation of attention to the cognitive task reduces gait performance (Agmon et al., 2014; Penati et al., 2020; Wrightson et al., 2020). Nonetheless, challenges also exist in this setting. For example, overground walking protocols have often been based on walking back and forth on a flat surface (McFadyen et al., 2017) and of short duration and distances (Hirashima et al., 2015; König et al., 2014). Yet, everyday walking consists of continuous dynamic adjustments, for instance making turns and crossing obstacles, for safe and successful adaptation to the environment and at longer distances (Bohm et al., 2015). Based on the abovementioned findings, overground walking under controlled conditions should be preferred especially when such conditions resemble everyday walking situations.

3.2.2 Devices for the acquisition of gait parameters

Examining gait characteristics in older adults enhances our understanding of gait control and helps us to better target preventive interventions, especially in terms of falls. Various gait analysis systems are employed to study gait and surpass the limits of visual observation. These approaches can be classified according to those based on non-wearable sensors or on wearable sensors, but also a combination of these two approaches is utilized (Beauchet et al., 2017; Muro-de-la-Herran et al., 2014). Non-wearable sensors are devices that are mainly based on image processing and pressure-sensitive floor sensors, such as the widely used GAITRite-system, which provides spatiotemporal parameters based on the recorded footfalls (Beauchet et al., 2017). This present thesis employed a non-wearable sensor device, which captures data of gait while the subject walks within or on a walkway. For the present work we adopted a relatively new device, the OptoGait-system, an open-field walkway floor-based photocell system, that enables spatiotemporal acquisition. Details of this instrument are reported in the methods section (see page 43).

3.3 Measuring dual-task effects: dual task costs versus relative differences

Dual-task paradigms are based on the notion that two simultaneously performed tasks interfere if relying on common functional and/or cerebral systems. In the case of walking and performing an attention-demanding task, the interference is based on the hypothesis of a common involvement of attention in both tasks. Quantification of the interference can be provided by two main methods: Calculations of *Dual Task Costs* (DTC), and by calculating the relative difference.

Dual Task Costs (DTC):

DTC is usually quantified for both tasks in a dual-task experiment. Calculating DTC can be done by the traditional formula, shown in percent, which is as follows:

$$\frac{dual\ task - single\ task}{single\ task\ x\ 100}$$

Here, negative DTC values indicate that performance deteriorated in the dual-task relative to the single-task.

Relative difference

Another method is to calculate the effects of a secondary task during dual-tasking by obtaining the relative difference in spatiotemporal parameters between single-task and dual-task walking (Muir et al., 2012). In other words, a simple calculation of the difference between gait parameters in single walking and gait parameters during dual-tasking can be used to reflect the effects of concomitant actions, i.e., single-walking *minus* dual-task walking. This approach allows for a straightforward understanding of the effects of the dual-task experimental situation and is a strategy recommended in the gait literature for an easier interpretation and clinical usage (Baker et al., 2009).

An important issue to highlight is that when applying the dual-task paradigm to the gait-cognition interaction, the most common interest has been to study the effects of the cognitive task on gait outcomes. The opposite, i.e., DTCs in the cognitive outcomes, has also been researched, but the main interest still remains on how cognitive operations disturb gait, and therefore the costs of the task are usually calculated on gait data as is the case in the present investigation.

3.3.1 Explanations of dual-task interference

Several explanations have been proposed to disentangle the dual-task interference. One such explanation points to *task complexity* causing increased attention load and thus exaggerated differences in performance due to competing resources (McDowd & Craik, 1988). Another hypothesis is based on a *general slowing factor* as an explanation of age-related differences (Verhaeghen & Cerella, 2002), which suggests that older adults' performance response speed can be predicted by a linear function related to task difficulty (Sit & Fisk, 1999). Both the complexity theory and the slowing explanation has been used to understand of age-related differences in single- and dual-task data.

Furthermore, simultaneous performance of two attention-demanding tasks not only causes a competition for attentional resources, but it also challenges the brain to decide how to prioritize the two tasks. This selection of a particular strategy for dual-task performance is consistent with the notion of *task prioritization* (Yogev-Seligmann et al., 2012). This selection of focus responds to postural threat and calls for adjustment. For example, if an individual must pay more attention to posture and stability to avoid falling, then performance on the cognitive task may be compromised; this may not be the case in a less threatening task/environment or for a person with greater postural reserve. This is also considered as "posture first"-strategy (Shumway-Cook et al., 1997; Yogev-Seligmann et al., 2012). Despite that, several studies have reported that undertaking a secondary task adversely affects gait in both cognitively intact and cognitively impaired individuals (Al-Yahya et al., 2011; Kelly et al., 2013). The underlying mechanisms of dual-task interference are still unclear.

Both the emergence of competition for attentional resources (Wickens & Kessel, 1980) and competition for information-processing neural pathways (Pashler, 1994) interleaves, and might share similar pathways of neural control. The recent literature has revealed that neurodegeneration in multiple systems that overlap with motor control systems and cognition lead to coexisting morbidities, even in healthy older adults. More specifically, networks connecting frontal and hippocampal areas have been suggested to explain effects in dual-tasking (Bishnoi & Hernandez, 2021; Hamacher et al., 2015; Mirelman et al., 2017). This piece of knowledge takes us further to the next section exploring common cognitive functions important in gait.

4 Cognitive functions related to gait

The importance of cognition in gait has been long acknowledged. Even the simplest walking condition, such as straight forward walking at a comfortable steady pace, involves important cortical networks and cognitive functions (Hamacher et al., 2015; Hausdorff et al., 2005; Jahn et al., 2010; Seidler et al., 2010). Therefore, establishing how specific cognitive functions affect gait in different situations is a current and important area of research in different populations.

Walking in daily life involves a complex integration of sensory and perceptual abilities, in addition to attentional and executive resources to effectively adapt to a dynamic environment. Being mobile, requires the engagement of an array of cognitive functions for multiple aspects such as navigating, planning, strategy-finding, and obstacle avoidance (Montero-Odasso & Camicioli, 2020). With the use of dual-task approaches, clinical and research evidence has established a close relationship between gait and cognition, where early disturbances in cognitive processes such as attention, executive functions, and working memory are associated with gait perturbations and these findings assist in the evaluation of mobility loss, falls, and progression to dementia. In the following section, a summary of research findings on cognitive functions involved in gait will be presented.

4.1 Attention and working memory

Both attention and working memory have been associated with gait. A well-functioning ability to sustain, shift and divide attention between factors in the environment and body is essential for successful walking in daily life (Woollacott & Shumway-Cook, 2002; Yogev-Seligmann et al., 2008). Definitions on attention vary, but generally the concept refer to capacities enabling an individual to focus on specific stimuli and to process stimuli (Lezak et al., 2012). Furthermore, there are various aspects of attentional capacities, such as selective, sustained, and divided attention, that are engaged during walking. Walking in the real world requires paying attention, which involves working memory, to various changing facets in the environment. Attention is also needed to recover from postural perturbations to avoid stumbles or falls. However, the type of attentional mechanism involved varies from one population of subjects to another. For instance, in younger adults' attentional abilities are at their highest functional levels, which implies that actions of any type can be performed easily. In contrast, in older adults both attention and working memory decline as a natural part of normal aging (Diamond, 2013; Ferguson et al., 2021) and thus, older adults experience more attentional difficulties while walking. For instance, attentional declines related to aging are associated with postural instability and risk of falls (Yogev-Seligmann et al., 2008). Both gait and cognition are affected by neurodegenerative disease and impaired cognitive abilities can reduce attentional resource allocation, which in turn compromise postural and gait stability (van Iersel et al., 2004).

Mobility in daily life often requires the simultaneous performance of tasks, i.e., dual-tasking, which is highly dependent of attentional resources. Further, working memory, consisting of a temporary storage and a limited processing system (Lezak et al., 2012), is of importance for simultaneous mobility actions. Under these circumstances, age-related declines in attention and working memory compromise the ability to perform tasks simultaneously (Yogev-Seligmann et al., 2008). Successful and, thus safe gait, is associated with more automatic control involving lower levels of attention and low gait variability (Beauchet et al., 2009). In contrast, with increased attentional demands or less attentional resources available, gait becomes more unstable, i.e., increased gait variability. It has been consistently demonstrated that an individual's focus of attention has an important influence on the performance of various motor skills in older adults, such as balance and postural control (Chiviacowsky et al., 2010).

4.2 Executive functions

Executive functions (EF) are referred to as an umbrella term consisting of higher order cognitive processes that modify information from many cortical sensory systems for the management of several cognitive processes, which include reasoning, working memory, attentional focus, cognitive flexibility, inhibition, and coordination of complex locomotor activities (Lezak et al., 2012). These integrative functions include both cognitive and behavioral aspects that are necessary for effective and goal-directed actions and for the control of attentional resources. The concept of EF is traditionally associated with cerebral networks situated in the prefrontal lobe, which are considered highly susceptible to age-associated changes (Diamond, 2013; Reuter-Lorenz & Cappell, 2008). Some reasons for these changes are the occurrence of white matter hyper-intensities, atrophy, but also changes in gray matter and reduced dopaminergic activity (Gunning-Dixon & Raz, 2000). Reductions in EF are common in aging, and occur even in healthy older adults (Jurado & Rosselli, 2007).

With regards to motor functions and gait, EF has become one of the most commonly cognitive aspects associated with gait dysfunction (Cohen et al., 2016; Montero-Odasso & Camicioli, 2020). Older adults rely heavily on EF when engaging in various motor actions such as walking (Al-Yahya et al., 2011), and the association between motor functioning and EF becomes stronger with increasing age (Amboni et al., 2013). In fact, even very early EF changes are related to gait disturbances in older adults (Herman et al., 2010; Yogev-Seligmann et al., 2008). The relationship between gait perturbations and EF deficits in aging has been attributed to degradation of overlapping brain regions and networks, dealing with the control of walking and EF, such as prefrontal cortex, frontoparietal, cingulate areas, and hippocampal-striatal networks (Ferguson et al., 2021; Li et al., 2018; Yogev-Seligmann et al., 2008).

There are specific situations where not only simple attentional mechanisms are engaged in the control of walking, but rather more EF are demanded. Executive function is often implicated in dual-task situations because subjects must walk and adapt to new and/or complex situations. These include cognitive situations demanding working memory, mental inhibition, and mental flexibility. Such situations implicate different contingencies like perceiving a walking context as challenging, adjusting balance to ensure a safe walk, or tackling obstacles. All these events have higher demands on executive control and increases gait variability, where individuals with poor executive functioning may not successfully estimate environmental hazards.

In parallel to the use of attentional tasks, EF tasks have also been used in the dual-task paradigms, for instance Stroop tasks (Patel & Bhatt, 2014). Not only have specific EF tasks been applied to study the EF-gait interplay but increasing the complexity of the walking protocol may also increase sufficiently the demands for executive functions. It is suggested that increased task complexity creates dual-task paradigms that are more sensitive at detecting subtle gait deficits in older adults (Kelly et al., 2010; Simoni et al., 2013). Another example involving EF in dual-tasking refers to walking challenging routes including turning and obstacle avoidance, which require more attention than straight-walking alone (Persad et al., 2008; Woollacott & Shumway-Cook, 2002).

To summarize, the application of concomitant tasks that tap on attention and executive functions in dual-task paradigms are the most suitable and recurrent tasks to assess specific gait effects in different study populations. Therefore, further developments in techniques aiming to improve our understanding of the mechanisms involved in gait deteriorations need to build up on EF and attentional demands.

5 Implementation of dichotic listening to a dual-task paradigm

A major challenge in current dual-task experiments is the lack of standardization of dual-task paradigms over study settings and task procedures, which results in a lack of validity and comparability between dual-task studies (Al-Yahya et al., 2011; Esmaeili Bijarsari, 2021). The existing variability in tasks and measures across the literature makes it evident that the choice of tasks has a profound effect on the dual-task data and that appropriate tasks relevant to the outcome of the experiment are needed. A fundamental part of research is the applicability of the results to real-world situations. Dual-task experiments are no exceptions and aim to address the ecological validity to various populations to assess everyday functioning. The term ecological validity refers to generalizability, the extent to which assessment results relate to behavior outside test environment, and representativeness, whether assessments do resemble current everyday functioning (Burgess et al., 2006).

Various assessments typically require discrete responses to single events and are conducted in carefully controlled environments. However, performance in the real world involves serial and parallel streams of tasks, frequently in disorganized and unpredictable environments. This juxtaposition of how subjects are assessed in the lab versus in the real-world context, may significantly limit the ecological validity of experiments (Schaefer, 2014). Thus, a major problem of many studies on age-related decreases in dual-task performance is the inconsistency of methods, in terms of both choice of cognitive task and walking procedure

Due to the limitations together with lack of specificity of cognitive tasks applied to dual-task paradigms, we propose the implementation of a non-invasive, robust, neuropsychological technique, namely the dichotic listening test (DL; Kimura, 1967).

5.1 What is dichotic listening?

Dichotic listening is an important method for studying interhemispheric function, callosal function, and brain lateralization and asymmetry in language processing (Hugdahl et al., 2009). Here, two different auditory stimuli are presented simultaneously to a subject's right and left ear and the subject must report the stimuli heard clearest after presentation. A common finding in DL studies is that right-handed individuals attend and report more from the right side, indicating a *Right Ear Advantage* (REA) (Bryden, 1988; Hugdahl et al., 2009; Kimura, 1967). This arises due to asymmetric ascending input of auditory information to the temporal lobe of the brain, confirmed by imaging studies (Hugdahl & Westerhausen, 2016). Here, input to the right ear ascends via contralateral connections through thalamus to the left temporal cortex where the dominant language center is located for most right-handed people (Corballis, 2003; Knecht et al., 2000). In the last decades, DL paradigms have included conditions that gain experimental control over attention by applying directed-attention procedures (Bryden et al., 1983), and the most well-known task of this type is *the Bergen Dichotic Listening Test* introduced by Hugdahl and Andersson (1986). The Bergen DL Test has the particularity to assess both bottom-up and top-down processing as it includes separately spontaneous attention DL condition, as well as conditions where volitional control of attention to one specific ear is demanded. These forced-attention conditions typically lead to an increase in REA when focus of attention is directed towards the right side and a reduction of the REA or shift to a Left Ear Advantage (LEA) when attending left-side is required. Thus, because different attentional focus is demanded, DL is considered a cognitive conflict situation involving higher cognitive control depicting executive function capacity (Hommet et al., 2010; Hugdahl et al., 2009). Considering the consequences of aging on cognitive functions, DL is particularly useful in studying attentional and executive processes in aging.

5.2 Dichotic listening and aging

General findings across DL studies with older adults reveal a more pronounced REA with increasing age in addition to reduced ability to maintain and sustain attention to the left side when instructed to do so (Andersson et al., 2008; Ianiszewski et al., 2021; Jerger et al., 1995; Westerhausen, Bless, & Kompus, 2015). Let us be reminded that focusing attention to the right ear is an efficient act for right-handers as the laterality of speech processing is in accordance with the anatomical decussation of the hearing system, causing synergy between bottom-up and top-down influences on REA (Hugdahl & Westerhausen, 2016). The REA is also strengthened in aging when voluntary control is directed towards the right ear. However, attending towards the left side is cognitively more demanding as the left-ear response conflicts with the automatic right-ear response taxing also inhibitory mechanisms. Older adults exhibit limitations in inhibitory mechanisms and EF and thus attending to the left side and simultaneously ignoring the right side is challenging (Westerhausen, Bless, & Kompus, 2015; Westerhausen, Bless, Passow, et al., 2015).

Few studies have investigated DL with individuals with AD and MCI. The limited data show that older adults with AD or MCI present an overall REA regardless of instruction of attention. Cognitively impaired older adults show a more prominent left-ear deficit compared to healthy older adults and furthermore, individuals with AD show more REA and left-ear deficit than individuals with MCI (Bouma & Gootjes, 2011; Duchek & Balota, 2005; Idrizbegovic et al., 2011; Utoomprurkporn et al., 2020). In spite of showing an evident REA, persons with AD or MCI denote significant declines in right-ear scores longitudinally (Häggström et al., 2018).

5.3 DL, hearing, and aging

DL has also been applied in older adults for the investigation of the central auditory processing (Gates et al., 2008). It is widely known that older adults have more difficulty in understanding speech, in particular in the presence of background noise, compared to younger adults. This may be due to peripheral age-related hearing impairment (ARHL) but also due to central processing dysfunction. Thus, DL is also a behavioral tool to assess Central Auditory Processing Disorder (CAPD) (Jerger & Martin, 2006; Musiek & Chermak, 2013). In addition, central and peripheral auditory function interacts with impaired cognition and is enhanced by ARHL (Idrizbegovic et al., 2011; Pichora-Fuller et al., 2016). Individuals with AD and MCI perform poorly on tests exploring central auditory processing (Idrizbegovic et al., 2011; O'Brien et al., 2021). However, this is difficult to study in older adults as increased AHRL obscure the interpretation of central auditory tests and DL has been proved useful in this matter. In addition, it has been suggested that central auditory dysfunction may precede the onset of clinical dementia in people with risk of AD and MCI (Gates et al., 2011; Häggström et al., 2018; Sardone et al., 2019), and hearing impairment is associated with greater risk of MCI and dementia (Fischer et al., 2016; Panza et al., 2015; Wei et al., 2017).

In sum, DL has not only been proved useful in the investigation of attentional and executive processes in older adults but also in the assessment of auditory dysfunction. This sheds light over potential connections and interactions between cognitive and central and peripheral auditory dysfunction and gait perturbations.

5.4 Can lateralized control of attention in DL influence gait asymmetrically?

An important feature of DL is being a measure for hemispheric asymmetry, as the auditory stimuli used in this test are language-related (Hugdahl, 2011). Because language production and processing in right-handed persons is primarily undertaken by the left brain hemisphere (Ocklenburg & Gunturkun, 2012), DL is a useful tool in the assessment of hemispheric ability. Nevertheless, hemispheric specialization exists for other functions, such as visuospatial processing or hand dexterity (Hirnstein et al., 2014; Ocklenburg & Gunturkun, 2012; Przybyla et al., 2013). The fact that the human brain has two distinct functional hemispheres brings the question as to how lateralized cognitive functions, as those assessed in DL, can influence body movements that require both sides of the body. For the present investigation, we refer to gait.

Gait is typically considered to be "*symmetrical*" in healthy people, which means that walking is characterized by almost identical movements of the bilateral limbs during a gait cycle (Sadeghi et al., 2000). As a rule, gait asymmetries (i.e., divergence between left and right lower limbs) have been considered to arise from disease, leg length discrepancies, and strength imbalances (Sadeghi et al., 2000). Both gait asymmetry and gait variability represent factors of instability and risk of falls (Montero-Odasso & Camicioli, 2020; Wong et al., 2020). Notwithstanding, gait asymmetries have also been reported in healthy individuals, including older adults (Sadeghi et al., 1997; Wong et al., 2020).

Thus, a main question to answer in the present thesis, is whether lateralized cognitive functioning, such as those demanded in DL, affects gait asymmetrically. In the past, DL has in fact been applied during dual-tasking together with finger-tapping. This situation entailed an asymmetric decrease in the right hand in young adults (Gadea et al., 1997; Wong-Goodrich et al., 2019). So far, the effects of DL on gait through a dual-task paradigm in overground walking have not been explored in any population. Therefore, a further matter that this thesis will address is whether such a scenario affects older populations with varying degree of cognitive impairment differently. It is well established that changes in hemispheric organization occur during aging (Reuter-Lorenz & Park, 2010), and for example, activity becomes less lateralized in older adults compared to younger adults, according to the hemispheric asymmetry reduction in older adults (HAROLD) model (Cabeza, 2002). In addition, age-related changes in hemispheric specialization of sensorimotor functions have been reported. According to the right hemi-aging model, left-hand abilities decline more rapidly with age than right hand (left hemisphere) abilities due to right hemisphere, more than the left hemisphere, being more prone to the adverse effects of aging (Dolcos et al., 2002). Moreover, motor asymmetries in upper extremities have been reported to show a decrease in preference towards the right side in both healthy older adults (Przybyla et al., 2011) and older adults prone to develop AD (Massman & Doody, 1996). However, less has been reported on gait as this activity has been considered rather "*symmetric*." Even though some data point to possible natural asymmetries in healthy persons (Sadeghi et al., 2000; Sunderaraman et al., 2019), it is still a matter of dispute whether these asymmetries arise as a function of increasing age (Nasirzade et al., 2017). Mainly, gait asymmetries have been shown to emerge during dual-task situations in older adults with gait impairments, for instance in those with Parkinson's Disease and cerebrovascular conditions (Ma et al., 2022; Plotnik et al., 2009; Sunderaraman et al., 2019; Yogev et al., 2007).

In sum, the present work seeks to answer whether performing DL during walking affects gait asymmetrically in different aging populations.

6 The interest of this thesis

Several indications point to important relationships between hearing loss, cognitive impairment, and gait deteriorations in aging. These factors affect each other in unknown ways and most probably, they are at the bases of risk of falling in older adults. On one hand, declines in cognitive functions contribute to age-related difficulties in auditory functions (Schneider et al., 2010), but the opposite has also been reported (Jayakody et al., 2018). On the other hand, age-related hearing loss is linked to declines in balance and walking, purportedly due to vestibular dysfunction (Lin & Ferrucci, 2012; A. Viljanen et al., 2009). A limited number of studies have addressed these three components (i.e., cognitive status, hearing ability, and gait) together in seniors.

Based on the above, the main goal of the present thesis is to introduce a novel dual-task paradigm, based on the application of the Bergen Dichotic Listening Test simultaneously to walking overground, to assess the interplay between hearing status, gait, and specific attentional demands in the auditory modality. In this way, we wish to understand the effects of spontaneous versus lateralized control of attention on gait. To our knowledge, no method has so far explored the mentioned factors under experimental conditions to understand their importance for risk of falling in older populations. Therefore, we will apply this new paradigm to three groups of participants: cognitively healthy older adults, elders with amnestic mild cognitive impairment, and healthy younger adults.

6.1 Interests of using DL in a dual-task paradigm with walking overground

Applying DL in a dual-task paradigm has the following interests:

a) The selected DL (i.e., Bergen DL Test) has three different attentional conditions based on same type of stimuli in the same sensorial modality. In other words, experimentally we control for same type of stimuli and same sensorial modality while we manipulate degree of difficulty of attentional capacities.

b) DL has three different difficulty levels related to each condition. First, spontaneous control of attention is assessed based on perceptual abilities or bottom-up reactions. Traditionally, this condition is regarded as natural and not demanding (Hugdahl et al., 2009). Thus, based on the literature, this condition can be regarded as little challenging. Secondly, sustained attentional control towards the right ear poses some extra difficulty to right-handed persons as it requires volitional control of attention. As it yields the right ear, the control is facilitated due to the right ear advantage (REA) described on pages 30-31. Thus, task difficulty increases at a moderate level. Finally, the highest degree of difficulty is assessed in the third condition, by demanding volitional control to the left ear. In this condition executive functioning is evaluated as right-handed persons need to inhibit their natural response of attending right-ear stimuli and focus on reporting stimuli from the least preferred ear. For older adults who experience declines and/or with impairments on EF, this condition is expected to be the one posing the highest difficulty load (Hommet et al., 2010; Hugdahl et al., 2009).

c) DL is considered valid as a test of auditory function, as it resembles a real-life social situation where listeners hear multiple speakers at the same time (Häggström et al., 2018). This situation brings *the cocktail party effect* into the dual-task paradigm, which is known to challenge central auditory processing (Cherry, 1953) which deteriorates during normal aging (Schneider et al., 2010).

d) DL while walking resembles the daily action of listening to a person to either the right or left side during walking, thus allowing for an experimental situation that is more ecologically valid. Applying DL in a dual-task situation creates a multi-tasking environment, that may reflect more appropriately how attentional processing occur in daily life with multiple information occurring at the same time and thus, this approach becomes more transferable to real settings.

6.2 Specific aims of this thesis

1) To investigate how spontaneous (i.e., Non-Forced DL condition) and lateralized attentional control (i.e., Forced Right and Forced Left DL conditions) affect quantitative and qualitative aspects of gait in:

    1.1 Cognitively healthy older adults (Paper I)

    1.2 Healthy young adults (Paper II)

    1.3 Older adults diagnosed with amnestic mild cognitive impairment (Paper III)

Quantitative gait effects (mean and Coefficient of Variation) will be evaluated on bilateral changes of conventional spatiotemporal measures of gait (i.e., effects on both lower limbs together), including gait speed, step length, stride length and step width. Qualitative gait effects will relate to possible gait asymmetries, i.e., differences of the spatiotemporal gait parameters on each lower limb separately.

2) To assess the moderating role of hearing loss on the effects on gait caused by DL in the older groups evaluated in this investigation, using Pure Tone Average (PTA). Both worst values and best values will be explored as covariate variables (Papers I and III).

We hypothesize that the different DL conditions will show different effects on gait in our study populations. We expect that spontaneous attentional control (i.e., Non-Forced, NF condition) will not cause important gait deteriorations. In contrast, we expect that the lateralized attention conditions (Forced Right, FR, and Forced Left, FL) will perturbate gait more than NF, possibly in terms of gait asymmetries, and especially the FL condition, which we assume will pose the heavier cognitive load across our groups.

Our expectations on possible effects on gait are related to bilateral effects of spatiotemporal gait parameters, specially, on gait variability. We hypothesize that older adults will show more gait disturbances than younger adults across all dual-task conditions, including single-walking. However, we assume that cognitively healthy seniors will show less perturbations than the older individuals with mild cognitive impairment.

Regarding DL performance, we expect younger adults to be better able to allocate attention and report more correctly from both right and left side when instructed to do so, displaying REA in NF and FR and a LEA in FL. In line with previous literature, we assume that the healthy older adults will report more from the right side, regardless of attentional instructions, and thus, show REA in all DL-conditions. We also believe that the MCI individuals will report less from left side in FL, in addition to report less correctly from the right side.

Of importance is the fact that we will not be able to assess the dual-task effect on DL outcomes as we on purpose did not include performing *only* DL in a “sitting-only” single-session. Being the first study that investigates asymmetries due to cognitive demands, we wished to assess naïve participants with no previous exposition to DL before performing it in the dual-task paradigm.

Lastly, due to the role of sensorial loss in aging, walking, and cognition, we expect that hearing loss will have an influence on the effects of dual-tasking in older adults. We expect that hearing loss may show important moderating effects on the quantitative and qualitative aspects of gait, but also affect the outcomes of the cognitive task.

7 Methods

The present thesis is based on three cross-sectional investigations. Data acquisition was performed at the Department of Psychology, UIT – Arctic University of Norway, Tromsø. All participants were involved in a larger umbrella project investigating motor functions and cognition.

Inclusion criteria

Inclusion criteria were being right-handed, native Norwegian speaker, above the age of 60 for the older groups, and between 18 and 40 years for the healthy younger adults. Furthermore, all participants had to show no depression, no diagnosis of orthopedic, musculoskeletal, neurological, other motor conditions or other co-morbidities likely to impact gait. For all the healthy older adults in all papers, a cut-off criteria on MMSE > 27 was applied to assure normal cognitive status (Petersen et al., 1999).

Exclusion criteria

As for exclusion criteria, we applied a cut-off of averaged pure-tone threshold higher than 45 dB on any ear and interaural asymmetry between ears of not >15 dB. These criteria were used for paper I and Paper III. For Paper II, participants with a hearing threshold of PTA of >25 dB were excluded to control for adequate hearing function. Further exclusion criteria were no symptoms of clinical depression or cognitive impairment or dementia which was ensured through questionnaires and interview.

Study samples

An overview of descriptive information about the different study samples in Paper I, II and III can be seen in Table 1.

Table 1.

An overview of gender, mean age, and mean educational years in the study samples in Paper I, II and III

	Paper I		**Paper II**		**Paper III**	
Participants	Young-old *n* = 38	Old-old *n* = 40	Young adults *n* = 40	Older adults *n* = 36	Controls *n* = 52	aMCI *n* = 43
Gender (m/f)	11/26	18/24	14/26	10/26	24/28	20/23
Age, years	65.4 (2.9)	**76.4 (4.8)***	**22.81 (2.86)**	**67.11 (5.09)**	70.90 (7.35)	71.19 (8.75)
Education, years	14 (3.5)	**12.3 (4.3)**	15.40 (2.27)	**13.59 (2.27)**	13.18 (3.55)	11.90 (3.91)

Note. aMCI = amnestic Mild Cognitive Impairment; m = male; f = female. Standard deviation reported in parentheses. (* $p \leq 0.05$, ** $p \leq 0.01$, *** $p \leq 0.001$)

Paper I

Seventy-eight older adults, age between 60 to 88 years (*M* = 71.1, *SD* = 6.6) were recruited to this study. These were divided into study groups based on age and hearing status. A score equal to or >25 dB on PTAs was used to classify those with moderate impaired hearing, while a score equal to or <24 dB was applied as cut-off to classify those having normal hearing acuity (Olusanya et al., 2019). Two groups were created: the Young-old group, which included individuals ≤ 70 years (*n* = 38), and the Old-old group (*n* = 40) with individuals that were ≥71 years old.

Paper II

For this article, two study groups were evaluated: a healthy young group and a healthy older group. The former consisted of 40 younger controls between the age of 19 and 35 years (*M* = 22.75 years, *SD* = 2.84), who were recruited mainly at campus of the University of Tromsø but also through words of mouth. The latter group of healthy older adults included 36 participants (*M* = 67.11 years, *SD* =5.09). Twenty-nine of these individuals were participants included in Paper I.

<u>Paper III</u>

A group of 60 individuals diagnosed with F06.7 Mild cognitive disorder (MCI), in accordance with the International Statistical Classification of Diseases and Related Health Problems (ICD-10), were recruited to the study. These individuals were diagnosed by senior geriatricians or senior neurologists and recruited from the Department of Neurology and Department of Geriatrics at the University Hospital of North Norway (UNN), Tromsø. In addition, a total of 58 age-matched healthy older adults were selected from Paper I and II, as the control group. Affiliation to MCI subtype was determined after ad hoc classifications. A final sample of 43 amnestic MCI subjects were identified (*M* = 71.19 years, *SD* = 8.75). As for the control group, 52 out of the original 58 older adults were retained after confirmation of being cognitively healthy (*M* = 70.90 years, *SD* = 7.35).

MCI classification in paper III

In Paper III, a classification method based on a thorough neuropsychological assessment of 3 cognitive domains was conducted. The method employed to assign MCI-participant into subtypes, i.e., amnestic MCI or non-amnesic, was the same as applied in Aarsland et al. (2009). Subjects were assigned to MCI subtypes in accordance with the neuropsychological criteria of MCI suggested by Jak et al. (2009) and Bondi et al. (2014), in which performance needs to be impaired on one domain by >1 SD below appropriate age norms. Cognitive results from a sample of cognitively healthy older adults (*n* = 103) from Northern Norway was used as normative data.

Based on this classification, individuals in the MCI group in Paper III were classified as amnestic MCI if they had greater impairment than 1 SD in the memory domain. With this classification method we also checked the cognitive status of the control group who was required to show performance on each of the assessed domains within 1 SD of the normative expectations.

7.1 Measures and materials

Background/Questionnaires

All participants completed a semi-structured interview to collect information about current and previous health status, education and professional history, and daily functioning. Participants were also screened for depression using the Beck Depression Inventory II, BDI-II (Beck et al., 1988); hand preference was confirmed with the use of the Annett Handedness Inventory (Briggs & Nebes, 1975) and foot preference was measured using the Waterloo Footedness Inventory (Elias et al., 1998). The Falls Efficacy Scale International (FES-I;Yardley et al., 2005) was applied to evaluate fear of falling in the older participants, in addition to the Norwegian version of the SF-36 questionnaire (Loge et al., 1998) to check the participants' subjective evaluation of their health status.

Neuropsychological examination

All the neuropsychological measures applied in this thesis were standardized tests, commonly used in clinical assessment and research (Lezak et al., 2012). First, all participants went through a general screening of cognitive status with the use of The Mini Mental Status Examination – Norwegian version (MMSE-NR; Folstein et al., 1975; Strobel & Engedal, 2008). Next, to obtain a thorough cognitive profile of all participants an extensive neuropsychological test battery was employed. This included measures of executive functions: Trail Making Test A and B (Reitan & Wolfson, 1995), Stroop Word Color Test (Golden & Freshwater, 1978) in addition to Digit Span Backwards (Wechsler, 2008); verbal functioning: Phonemic fluency - the Controlled Oral Word Association Test (COWAT; Benton, 1967), Semantic Fluency (Newcombe, 1969), and Vocabulary (Wechsler, 2008) were administered; and visuo-constructive abilities: The Clock Drawing Test (Shulman, 2000) and Block Design (Wechsler, 2008) were applied. To examine memory, Logical Memory immediate and delayed recall (Wechsler, 1997), as well as Digit Span forwards (Wechsler, 2008) were administered. As this doctoral work is a part of an umbrella project examining psychomotor changes in aging, the tests

Finger Tapping Task and Grip Strength (Reitan & Wolfson, 1985) were applied as a measure of neuromuscular speed but only in Paper I.

Audiometric Screening

All participants underwent pure-tone audiometry for the frequencies 250, 500, 1000, 2000, 4000, 6000, and 8000 Hz using a Madsen Itera II (GN Otometrics, Denmark) audiometer. We used the WHO definition of hearing loss of >25 dB for the frequencies 500 Hz - 4000 Hz (Olusanya et al., 2019). Also, we calculated the average hearing sensitivity reflected by calculating the "pure tone average" (PTA) from the hearing thresholds of the frequencies 500, 1000, 2000 and 4000 Hz.

Inclusion and exclusion criteria for hearing stats varied in the different studies depending on the specific aims. In Paper I, an interaural difference larger than 15 dB was used, and a PTA equal to or higher than 25 dB was applied to classify participants. Those with normal hearing thresholds had values ≤25 dB, while those mildly impaired showed values ≥25 dB. In Paper II, a threshold of >25 dB was an exclusion criterion to retain only individuals with normal hearing. In Paper III, a threshold of 45 dB was applied as inclusion/exclusion criterion. This value was decided to include as many MCI participants as possible, since hearing loss is highly prevalent in this condition (Wei et al., 2017). At the same time, this threshold assures that only persons with mild and slightly moderate hearing loss (who were still able to perceive auditory stimuli) were recruited for the investigation.

Calculations of PTA were conducted for each ear and designation for "Best" (i.e., the lowest threshold) and "Worst" (i.e., the highest threshold) was settled. PTA Best is assigned to the ear with lowest decibel-value. This value, being the lowest functional threshold, indicates auditory compensation. On the other hand, PTA Worst, which points to the ear with highest threshold in dB, indicates actual auditory dysfunction (Linssen et al., 2014). In Paper I and Paper II, PTA Worst was applied as a covariate, while in Paper III, PTA Best was applied as covariate. Selection of PTA type depended on ad hoc solutions based on the most relevant results obtained after controlling for these values.

Gait

Spatiotemporal parameters were acquired using the OptoGait System (OptoGait, Microgate, Bolzano, Italy). The system quantifies gait parameters using photoelectric cells that register interference in light signals. The sensors in the OptoGait system are placed over ground creating a 7 m x 1.3 m wide rectangular corridor wherein subjects walk in loops counterclockwise. Ninety-six LED diodes are positioned on each bar one centimeter apart at three millimeters above the ground. When subjects pass between two bars positioned in parallel with the ground, transmission and reception are blocked by their feet. Timing, size, and distance are sensed, and spatiotemporal parameters are automatically calculated. Data were extracted at 1000 Hz and saved on a PC using OptoGait Version 1.6.4.0 software. The OptoGait system has proved to be a highly reliable and valid instrument (Lee et al., 2014; Lienhard et al., 2013).

Parameters assessed

Gait parameters examined and analyzed were gait speed, step length, stride length, and step width, for both feet (i.e., bilateral) and by foot (lateralized measures). These parameters were selected as they represent the pace measures of walking, which have been reported to be sensitive to executive dysfunction (Hollman et al., 2011; Verghese et al., 2007). We used linear measures for each parameter including the mean (*M*) and the coefficient of variation (CoV, based on the formula [SD/mean] x 100%).

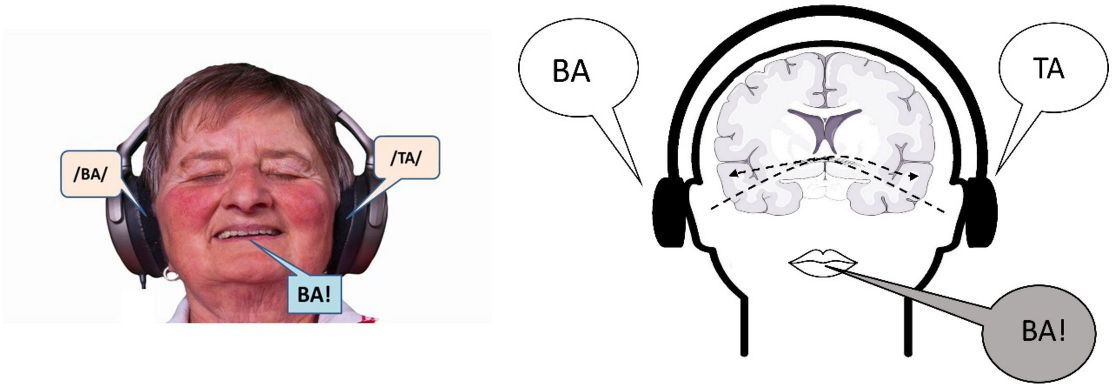
Dichotic Listening

We applied the Bergen Dichotic Listening Test (Hugdahl & Andersson, 1986). The paradigm consists of six consonant-vowel (CV) presentations: /ba/ /ta/ /pa/ /ga/ /da/ /ka/ and where the different CVs were presented simultaneously and randomized, each syllable of 350 milliseconds duration. The syllables were paired with each other in all possible combinations to form 36 different syllable pairs. From these, six homonym pairs (e.g., ba–ba) were included in the test as perceptual control. The CVs were read by a Norwegian-speaking male voice with constant intonation and intensity with a time interval of 4000 milliseconds. The total duration of each DL condition was three minutes. DL-responses were recorded with a digital voice recorder hanging around the participants' neck. The syllables were presented using wireless noise-cancelling headphones. E-prime 2.0 Software (Psychology Software Tools, Inc., Pittsburgh, PA, USA) was used to present the stimuli. The DL procedure has three conditions: The Non-Forced condition (NF) was always performed first, where participants were instructed to report the syllable heard the clearest. For the next conditions, participants were instructed to pay attention and loudly report stimuli from either right (Forced Right, FR) or left (Forced Left, FL) side, while ignoring information from the opposite ear. The order of the FR and FL were counterbalanced across subjects depending on their ID number. Participants with ID numbers that were odd numbers received FR before FL. For illustration of the DL, see Figure 2.

Figure 2.

Illustration of the DL performance (1) and the decussation of auditory pathways (2)

(1) **(2)**



Note. The DL mechanisms illustrated in (2) as described on pages 30-31

7.2 General procedure

For all papers, data collection was performed at the Department of Psychology, University of Tromsø. The duration of the whole procedure was about three hours in a sound-attenuated room. For the older adults, testing sessions were divided into two parts to avoid fatigue. All participants were initially interviewed about demographic background and health history. Afterwards, all subjects underwent audiometric screening to settle their hearing status and assure their hearing to be adequate to perform the DL test. Then, the participants completed questionnaires about depression, handedness, footedness, health status, and fear of falling. Next, neuropsychological testing was conducted. Finally, the dual-task experiment was performed in a rectangular shaped, sound-attenuated room. The following section will describe this part in detail. An overview for methods applied in this current work is provided, see Table 2.

Table 2.

Overview over materials and measures in Paper I, Paper II, and Paper III

	Paper I	**Paper II**	**Paper III**
Participants/groups	Young-old <70 years *n* = 38 Old- old >71 years *n* = 40	Young adults *n* = 40 Old adults *n* = 36	Cognitively healthy older adults *n* = 52 Amnestic MCI *n* = 43
Time of data acquisition	2013-2016	2013-2016	2013-2016 (healthy controls) 2017-2019 (MCI participants)
Background variables	BDI-II SF-36 Handedness Questionnaire Foot Preference Questionnaire FES-I	BDI-II SF-36 Handedness Questionnaire Foot Preference Questionnaire	BDI-II SF-36 Handedness Questionnaire FES-I MMSE
Audiometric measures	Hearing thresholds on 250 Hz, 500 Hz, 1000Hz, 2000Hz, 4000 Hz, 6000 Hz and 8000 Hz.	Same as Paper I	Same as Paper II
Neuropsychological measures reported	MMSE, TMT A and B, Stroop, Phonemic Fluency, Semantic fluency, Logical memory I and II, Digit Span forwards & backwards, Block Design, Vocabulary, Purdue pegboard, Finger-tapping, Grip strength	MMSE, CDT, TMT A and B, Stroop, Phonemic Fluency, Semantic fluency, Logical memory I and II, Digit span forwards & backwards	CDT, TMT A and B, Stroop, COWAT, Semantic fluency, Logical Memory I and II, Block design, Digit Span forwards & backwards,
Gait measures assessed	Mean & CoV – bilateral and lateralized outcomes for: Stride length Step length Gait speed Step width	Mean & CoV – bilateral and lateralized outcomes for: Step length Gait speed Step width	Same as in Paper II

Note. MCI = Mild Cognitive Impairment; BDI-II = Beck's Depression Inventory 2nd version; SF-36 = The Short Form Health Survey; FES-I = The Falls Efficacy Scale International ;MMSE = Mini Mental Status Examination; Hz = Hertz; TMT = Trail Making Test; CDT = Clock Drawing Test; PTA = Pure Tone Advantage; COWAT = Controlled Oral Word Association Test;; CoV = Coefficient of Variance; DL = Dichotic Listening; LI = Laterality Index; DTC = Dual Task Cost

7.2.1 The dual-task experiment[1]

All participants were evaluated for single-walking as well as three dual-task conditions, i.e., four conditions: (1) only walking, (2) walking and performing the NF condition, (3) walking and performing the FR, and finally, (4) walking while performing FL. No previous training was conducted beforehand as we aimed to obtain results from unexperienced individuals exposed to a single trial of the experiment. All subjects were asked to walk counterclockwise in a self-selected, comfortable walking speed.

Prior to the conduction of the dual-task conditions, the experimenter explained to the participants to walk the same walking route as in the Baseline-condition, but this time while conducting the DL procedure. The participants were given a demonstration trial of the DL procedure and were required to listen and respond to three CV-syllables while wearing headphones, without walking, to ensure comprehension of the instructions, see Figure 2. Careful adjustment of the volume was ensured for each subject. A digital recorder was hung around the participants' neck to record the participants' answers and the experimenter attached the microphone appropriately. The participants were also shown a sheet of paper with the six syllables used in the DL test to clarify the sort of stimuli presented in the experiment. A similar sheet was attached to the wall at the end of the walkway for reminding which stimuli to be expected. During the experiment, the oral responses were also written down by the experimenter. It is important to highlight that the experimental situation did not open for any beforehand task prioritization, but the instructions rather denoted equal prioritization for both tasks. In all dual-task conditions, the DL test was initiated simultaneously as the test subject moved their foot to initiate walking, this by a verbal cue from the experimenter. An illustration of the procedure is displayed in Figure 3.

Baseline condition (only walking). In the Baseline condition, participants were asked to walk for one minute within the corridor to collect baseline measurements without performing the cognitive task.

[1] The procedure description is practically the same as the one presented in Paper III

The OptoGait system starts recording gait as the subject took the first footstep, initiated by a verbal signal by the experimenter. The Baseline-condition was shorter, one minute long, than the rest of the dual-task conditions to assure that subjects did not get tired or lightheaded while allowing acquisition of sufficient gait data to obtain spatiotemporal parameters in the control condition.

DL Non-Forced condition. In the first dual-task condition, subjects were asked to walk continuously and execute the DL task as accurate as possible. The instructions given were: "*We kindly ask you to say aloud the syllable you hear the clearest every time you hear the stimuli while you walk in rounds in the designated area as previously demonstrated. Please keep walking and report the syllables during the entire trial as well as you can.*

DL Forced-attention conditions. The following two conditions were counterbalanced based on whether participant number was an odd or even number, where the FR condition came before the FL when ID number was odd number. In the FR condition, the participants were reminded that again, various they syllables will be presented to both ears, but that this time they were required to report loudly only the syllables presented to the right ear. In the FL conditions the same instructions yielded, but here subjects were required to only report the syllables presented to the left ear.

Figure 3.

Source: Gorecka et al. (2021)

Statistical Analyses

All statistical analyses were performed with IBM SPSS 26 (IBM, Corp., Armonk, N.Y., USA). An overview over the statistical analyses can be seen in Table 3. Group comparisons for demographics, background variables, neuropsychological tests and questionnaires were performed with independent t-tests.

Table 3.

An overview over the statistical analyses and data used in Paper I, Paper II, and Paper III

Statistics	**Paper I**	**Paper II**	**Paper III**
Data: demographics, background variables, neuropsychological variables	X	X	X
Independent T-tests:	X	X	X
GAIT			
Raw scores DTC (Baseline – DL Condition) Percent change from Baseline	X	X X X	X
Correlations with DL	X		
Repeated measures ANOVA on raw data	X	X	X
Bilateral RMANOVAs			
2 Group x 4 Condition	X	X	X
2 Group x 3 Condition		X	
Lateralized:			
2 Group x 4 Condition x 2Foot	X	X	X
2Group x 3 Condition x 2Foot		X	
DICHOTIC LISTENING			
Repeated measures ANOVA Correct responses: 2 Group x 3 Condition x 2 Ear	X	X	X
Laterality index, Errors, Homonyms: 2 Group x 3 Condition	X		X
Repeated measures ANCOVA			
PTA Worst	X	X	
PTA Best			X

Note. DL = Dichotic Listening; LI = Laterality Index; DTC = Dual Task Cost; RMANOVA = Repeated Measures Analysis of Variance; ANCOVA = Analysis of Covariance; PTA = Pure Tone Average.

Analyses for DL

For DL, a series of factorial analyses of variance with repeated measures with Group as between-subjects, and with Condition and Ear as within-subjects factor for the analyses of correct responses. For the measures of errors, laterality index, and homonyms, 3 Condition x 2 Group was applied in repeated measures ANOVA.

Analyses for gait measures

For the gait measures, a serial factorial analyses of variances with repeated measures were performed on the raw data. Mean values and CoVs were obtained for both feet (bilateral outcomes) and per foot (lateralized outcomes). This was due to the investigation of possible asymmetries in gait caused by DL. For the bilateral analyses, mixed-ANOVAs were conducted with 4 Condition (Baseline, NF, FR, FL) as within-subjects factor x 2 Group. For the lateralized analyses, we used three-way ANOVAs using 4 Condition x 2 Foot x 2 Group design.

Specific analyses for Paper I: Correlations

In Paper I, Pearson's correlations between correct DL responses and lateralized gait measures were performed to assess the relationship between these variables by DL condition.

Specific analyses for Paper II: DTC and percentage of Baseline.

For Paper II, two calculations of DTC were deemed necessary to compare gait outcomes: DTC and percent of Baseline. First, the absolute differences in raw scores for mean and CoV for both bilateral and lateralized gait outcomes were calculated. The DTCs were calculated by determining the difference between scores from single-task and gait parameters in the three dual-task conditions, e.g., results on Baseline *minus* a dual-task condition, to allow for a straightforward understanding of the dual-task effects and is commonly applied in clinical settings. This was performed due to unexpected findings in the raw gait data of the younger adults. See General Results for complete exposition of this matter. At the same time, we also calculated the percentage of Baseline values, which allowed us to appraise the proportion of change performance affected by the cognitive task. Both calculations are complementary. Percentage of Baseline values were calculated by dividing each gait parameter under each DL condition by baseline gait scores and multiplied by 100, thus expressed in percent.

The DTCs in Paper II were analyzed with mixed repeated measures ANOVA, i.e., 3 Condition (Baseline - NF, Baseline - FR, Baseline - FR) as within-subjects factor x 2 Group (Young, Old) as between-subjects factor.

Moderating effects of hearing status

To test the moderating effects of hearing loss on both DL and gait, PTA Best (Paper III) and PTA Worst (Paper I and II) were applied as covariate in a series of ANCOVAs.

General analyses

If significant omnibus test were found, univariate tests were performed. With significant interactions, simple main effects analyses were performed. Significant interactions and main effects between groups were followed up by appropriate post-hoc analyses. When sphericity assumptions were not met, Greenhouse-Geisser corrections were chosen. The Bonferroni correction was applied in all studies for protection of multiple comparisons.

Ethical Considerations

The studies involved in this thesis are a part of an umbrella project of motor functions and cognition in aging approved by the Regional Committee for Medical and Health Research Ethics – REK (2009/1427). All participants received information in written form and orally upon arrival about the study about voluntary participation, anonymity, opportunity of withdrawal, and signed an informed consent in accordance with the Declaration of Helsinki. Older adults are considered potentially vulnerable participants and fatigue during test sessions and potential dizziness in walking conditions had to be taken into account. To ensure the participants' comfort, several breaks were provided during cognitive testing sessions and between walking/dual-task conditions. For individuals with cognitive impairment, test sessions and administrations were adjusted to take place on additional days if necessary.

8 General Results

In this section, a presentation of the main findings across the three papers will be presented. To begin with, an overview over significant group differences on neuropsychological results, demographic measures, and audiometric parameters in Paper I, Paper II, and Paper III are presented in Table 4.

Table 4.

Overview over significant group differences on audiometric measures, neuropsychological results and demographics in Paper I, Paper II, and Paper III

	Paper I		**Paper II**		**Paper III**	
	Young-old (*n* = 38)	Old-old (*n* = 40)	Young (*n* =40)	Old (*n* = 36)	Controls (*n* = 52)	aMCI (*n* = 43)
Demographics:						
Age (years)	**65.4**	**76.4*** **	**22.81**	**67.11** **	70.90	71.19
Education (years)	**14.0**	**12.3***	**15.40**	**13.59***	13.18	11.90
Handedness	20.7	19.8	**16.63**	**21.06***	**19.88**	**22.02***
MMSE	29.08	28.33	29.28	28.92	**29.27**	**25.67*** **
Audiometry:						
PTA Best (dB)	**17.12**	**26.6*** **	**5.85**	**13.59*** **	**21.53**	**29.37*** **
PTA Worst (dB)	**20.38**	**31.9*** **	**9.26**	**16.19*** **	**27.45**	**35.37** **
Neuropsychological battery						
TMT A (sec)	**34.85**	**42.20***	**25.30**	**35.50***	**36.07**	**56.64*** **
TMT B (sec)	**75.36**	**107.9** **	**65.07**	**80.04***	**92.10**	**195.67*** **
Stroop Word	**91.92**	**78.53*** **	**107.38**	**89.08*** **	NR	NR
Stroop Color	**64.97**	**55.25*** **	**86.83**	**62.19*** **	NR	NR
Stroop CW	**34.45**	**27.10*** **	**59.73**	**33.83*** **	**32.52**	**27.63***
Log Memory I	10.39	10.58	11.54	11.36	**23.93**	**8.16*** **
Log Memory II	14.42	13.53	**10.54**	**15.22** **	**27.56**	**7.39*** **
Digit span						
Forwards	**9.11**	**8.08** **	9.78	9.08	**8.90**	**7.37*** **
Backwards	8.11	7.50	8.90	8.25	**8.08**	**6.37*** **
Block Design	36.00	32.72	NR	NR	**38.23**	**27.61*** **
CDT	NR	NR	6.95	6.81	**6.93**	**6.10** **
COWAT						
Correct answers	13.67	12.02	NR	NR	**13.83**	**11.16** **
repetitions	**0.37**	**0.60***	NR	NR	NR	NR
Semantic fluency			NR	NR	NR	NR
Correct answers	**17.49**	**15.06** **	NR	NR	**16.54**	**12.78*** **
Pegboard						
Right	**13.08**	**10.58*** **	NR	NR	NR	NR
Left	**11.95**	**10.23*** **	NR	NR	NR	NR
Both	**10.16**	**8.33*** **	NR	NR	NR	NR
Assembly	**5.92**	**4.70*** **	NR	NR	NR	NR
Grip strength						
Right (kg)	**31.75**	**38.78** **	NR	NR	NR	NR
Left (kg)	**30.54**	**37.39** **	NR	NR	NR	NR

Note. PTA = Pure Tone Average; MMSE = Mini Mental Status Examination; TMT = Trail Making Test; CW = Color-Word interference; CDT = Clock Drawing Test; COWAT = Controlled Oral Word Association Test; Log Memory = Logical Memory (* $p \leq 0.05$, ** $p \leq 0.01$, *** $p \leq 0.001$). NR – Not Reported.

As a whole, we can observe that the main differences in Paper I between the two older groups emerged for sensory-motor tasks, executive functions, short term memory, and complex verbal tasks, as well as for years of education and audiometric measures. For Paper II, education, handedness, audiometric data, as well as tasks for executive function and delayed memory, were observed to differ significantly between the younger and older samples. Finally, in Paper III, all measurements turned out to be significantly different between cognitively healthy older controls and aMCI subjects.

In sum, these data help us understand the sensory-motor and cognitive profile of the individuals participating on each part of the investigation. In the next section, a summary of results by paper will be presented. Thereafter, in order to gain insight into how the three DL-conditions affected gait will be shown by type of attentional demand under dual-tasking. Lastly, a summary of DL-results across the different papers will be displayed.

8.1 Results for gait by paper

Paper I

The aims of this paper were to assess how age-related hearing loss and lateralized auditory attention affected overground walking in community-dwelling older adults by performing dichotic listening concomitantly. Two samples of cognitively healthy older adults of different age ranges were assessed (Young-old $\leq$ 70 years vs. Old-old $\geq$ 71 years). We expected that the different attentional conditions in DL would have different effects on gait and that particularly paying attention to the left side would perturbate gait the most. Also, we wished to understand whether degree of hearing loss had a moderating effect on the results.

Main findings in this study showed that lateralized focus of attention altered mean step width, mean gait speed, and stride length CoV asymmetrically in all healthy older adults. Asymmetrical increments in stride length variability of the right limb were seen in both groups even after controlling for hearing status. These results were seen in the forced attention-conditions. Also, we found asymmetrical gait perturbations in the Old-old Group on gait speed during NF condition. Here, older adults reported higher number of right-ear responses while they had slower speed on the left foot. Correlation analyses showed that attending left-ear stimuli was associated with increased CoVs. Results imply that attending left-ear information increases the risk of falls. However, CoV also increased while attending right-ear information, but to a lesser level. Thus, listening to the right side did not compromise gait deleteriously, but secured posture and preserved walking. Hearing loss, even mild, modulated the effects on gait during dual-task conditions showing several gait effects disappearing, further implying that hearing loss masks dual-task effects on gait. Our findings clearly show an association between hearing loss and gait.

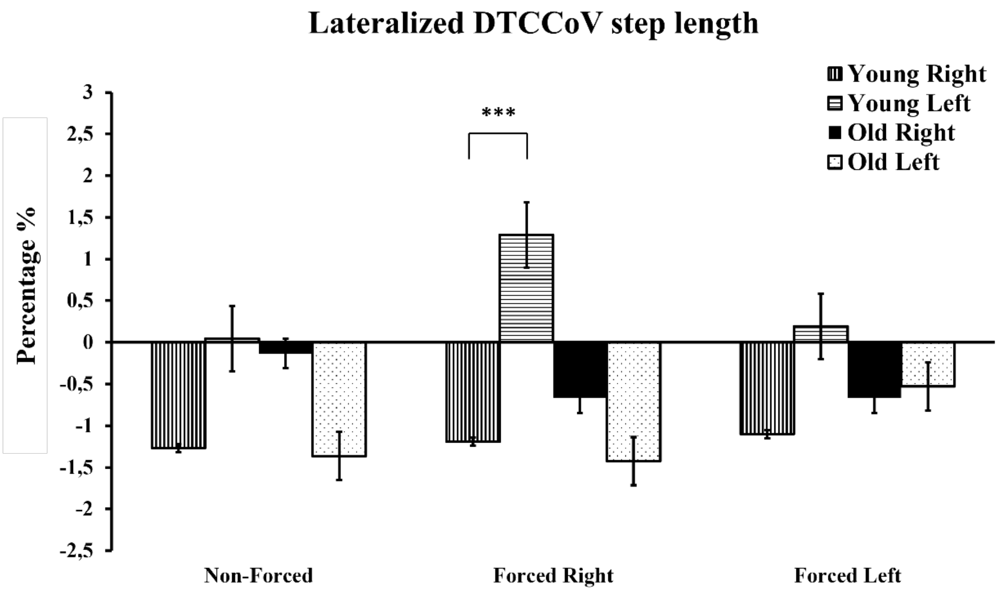
Paper II

In Paper II, we applied the same study procedure as in Paper I, but now comparing healthy younger adults (mean age = 22.81, *SD* = 2.86) and healthy older adults (mean age = 67.11, *SD* = 5.09). We aimed to investigate possible age-related differences on the way the dual-task paradigm affected gait procedures from a life-span developmental perspective. Importantly, we investigated in this paper the differences between young and older adults based on *dual task costs* (DTC) and on the percent change from Baseline across DL conditions. We decided to employ these calculations due to unexpected findings where the younger sample displayed lower baseline raw gait data than older adults (see Table I and Table II in Supplementary Material of Paper II). Initially, we expected that gait would not be compromised by DL in the young group and that younger adults would outperform the older adults across measurements. However, a first view on the raw data for gait showed the contrary. It happened that younger adults displayed slower gait speed than older adults across dual-task conditions, which was completely unexpected. Therefore, in order to appraise the real nature of these findings we calculated DTCs and percent change from Baseline. These approaches demonstrated in fact, similar results in both groups for bilateral mean values for gait speed. Nevertheless, the cost of the dual-task situation was somewhat harder for younger adults when bilateral step length (mean) was tested.

Otherwise, no group differences were registered related to variability (CoV) of bilateral gait parameters. The most important finding of this paper was observed on the lateralized analyses of gait in younger adults. Younger participants displayed more DTC changes on both mean and CoV values from step length, especially on the left foot, during the FR condition, see Figure 4.

Figure 4.

Mean and SEM for DTCCoV for step length by foot



Note. SEM = Standard Error of Mean; DTCCoV = Dual task cost for CoV (coefficient of variability); *** $p < 0.001$ Nota bene: This figure is the same as depicted in Figure 6 in Paper II.

Regarding the percent of Baseline findings, this measure points to the magnitude of adjustments occurring. Thus, the most important result here pointed to changes on step length (Mean and CoV) in both groups. Specifically, mean values in the young group showed a decrement of CoV in the forced attention-conditions while data from the older adults revealed increment in CoV that tended to be asymmetrical. Although there was no significant interaction, we observed a trend where older adults showed an increase in step length variability across all DL-conditions, especially on their left foot, see Table 5.

Table 5.

Average percent of Baseline by DL condition for lateralized gait parameters (by foot)

	CONDITIONS						
	Non-Forced		Forced-Right		Forced-Left		
	Young	Old	Young	Old	Young	Old	Two-way ANOVA, *p-value,* (η^2_p)
	M (SD)	*M (SD)*	*M (SD)*	*M (SD)*	*M (SD)*	*M (SD)*	Condition/ Foot /Interaction / Group
Mean							
Step length R%	94.8 (4.0)	99.0 (15.8)	93.5 (5.9)	99.8 (2.6)	93.8 (5.7)	100.0 (0.0)	
Step length L%	95.8 (5.3)	101.3 (3.4)	94.9 (5.9)	99.9 (2.4)	94.3 (6.2)	100.0 (0.0)	NS / NS / NS / **0.0001 (0.29)**
Gait speed R%	93.4 (8.3)	94.8 (12.9)	90.7 (11.1)	90.7 (9.6)	90.1 (11.4)	90.1 (8.6)	
Gait speed L%	93.2 (8.7)	93.0 (9.2)	90.4 (11.4)	90.7 (9.5)	89.4 (11.6)	90.1 (9.0)	**0.001 (0.25)** / NS / NS / NS
Step width R%	101.3 (28.5)	95.3 (141.4)	102.3 (28.4)	102.6 (114.8)	106.0 (33.9)	113.4 (127.3)	
Step width L%	101.6 (25.1)	126.0 (97.2)	101.4 (27.4)	126.4 (98.9)	105.8 (24.3)	130.7 (106.4)	NS / NS / NS / NS
CoV%							
Step length R%	111.1 (26.6)	110.5 (41.4)	111.2 (29.5)	126.8 (74.7)	109.7 (24.1)	131.7 (74.2)	
Step length L%	103.5 (25.1)	149.0 (98.3)	95.8 (21.1)	151.7 (101.5)	103.2 (25.8)	151.4 (95.9)	NS / NS / NS / **0.004 (0.10)**
Gait speed R%	102.5 (17.2)	161.5 (171.1)	101.0 (16.11)	162.2 (204.8)	100.2 (13.4)	208.7 (291.3)	
Gait speed L%	107.6 (48.2)	160.1 (124.6)	102.2 (28.4)	177.7 (245.0)	100.7 (15.5)	193.4 (272.5)	NS / NS / NS / NS
Step width R%	101.0 (0.2)	101.0 (0.3)	101.0 (0.22)	101.1 (0.5)	101.0 (0.2)	101.0 (0.1)	
Step width L%	101.0 (0.2)	101.0 (0.3)	101.0 (0.2)	101.2 (0.5)	101.0 (0.2)	101.0 (0.1)	NS / NS / NS / NS

Note. M = mean; *SD* = standard deviation; CoV = Coefficient of Variation; Interac. = Interactions; NS = Non-Significant. CoV = Calculated with the formula: [SD/mean] x 100%; Nota bene: This table is the same as Table 5 in Paper II.

All in all, by using the two methods of calculating DL's effect on gait, we showed that the most important alteration of the dual-task paradigm was on step length variability. Furthermore, this paper demonstrated that performing DL also evoked lateralized effects in healthy young individuals.

As a final remark for this paper, it is necessary to pinpoint that the role of hearing was not evaluated for gait outcomes since we evaluated subjects with normal hearing ranges. For DL, some significant interactions were not further present when controlling for hearing status. However, group differences on DL performance remained present even after controlling for hearing level, which indicates a real difference of cognitive abilities during executing of DL under dual-tasking.

Paper III

The aims of Paper III were to investigate gait perturbations comparing aMCI and cognitively healthy older adults by applying the same dual-task paradigm as in Paper I and Paper II. The main interest was to determine whether spontaneous versus volitional focus of attention in aMCI show quantitative or qualitative impairments on gait. Based on the findings of Paper I and II, we expected both quantitative and qualitative gait changes in the aMCI group which would reflect more dysfunction in this group compared to healthy controls, especially in the NF condition and in the FL condition. Furthermore, we expected that hearing difficulties in aMCI would moderate the effects DL induce on gait.

As expected, the aMCI group showed that DL compromised all quantitative gait parameters on bilateral mean values, i.e., shorter steps, slower gait speed, wider step width, in addition to increased step length variability and gait speed variability. Also, significant larger variability was seen on gait speed and step length in the forced attention-conditions. No further differences between the groups were seen until controlling for hearing acuity. After controlling for hearing status, qualitative changes emerged. First, a slight asymmetry on step length variability in the left foot was present in aMCI during NF but not in the other DL conditions. In contrast, increased step variability in the right foot during the forced attention-conditions was seen in the group of cognitively healthy controls. These effects were only revealed after controlling for hearing status, which suggests a moderating role of hearing loss on gait asymmetries. The DL task caused more asymmetries in the healthy controls than in the aMCI individuals suggesting DL having a differential effect in these study groups.

8.2. Effects of spontaneous vs. volitional DL attentional demands on gait parameters

In order to answer the central questions of investigation, in this section we present a summary of findings showing what happened to gait when spontaneous attention versus lateralized control of attention was required in the various samples.

a) How does spontaneous attention (Non-Forced Condition) affect gait?

Paper I

Bilateral results (both limbs*)*: When spontaneous attention was required, the Young-old group exhibited longer steps length mean and stride length mean in NF compared to the Old-old group. After controlling for hearing status – a main effect of Group on step width emerged showing that the Old-old group had wider step width than the Young-old group. The Old-old group showed higher step length variability and gait speed variability, which maintained after controlling for hearing status, see Table 6.

Lateralized results (by foot): An interaction between Condition x Group x Foot was seen on gait speed in the Old-old group showing that this group had slower gait speed on the left foot during NF. Also, during the NF-condition we found that both groups had asymmetrical stride length variability. In particular, there was an increased CoV on right foot in the Old-old group. Pearson's correlations between lateralized gait values and right-ear versus left-ear responses in the DL test were performed. In the NF condition, right-ear responses were positively associated with mean step length and mean gait speed on the left foot.

Paper II

Bilateral results***:*** The DTCS of the mean in gait speed increased in both groups while DTCs of CoV in step length was clearly more affected in the young group. Percent of Baseline results showed that older participants had an increment in step length variability in the NF condition, while younger adults showed reduced mean values of step length.

Lateralized results: The main finding on DTCs showed that the younger group had a higher increment in step length variability of right foot during the NF condition. The percent of Baseline calculations revealed a trend in which the older group increased step length variability of their left foot, albeit this finding was not significant.

Paper III

Bilateral results***:*** The aMCI group displayed higher CoVs on all gait measures than controls.

Lateralized results: The aMCI group exhibited slightly higher CoV on step length of left foot during the NF Condition.

Table 6.

Overview of effects of NF on gait parameters in Paper I, Paper II and Paper III.

SPONTANOUS ATTENTION (NON-FORCED CONDITION)							
	Paper I		**Paper III**		**Paper II**		
	Young-old (*n* = 38)	Old-old (*n* = 40)	Controls (*n* = 52)	aMCI (*n* = 43)		Young adults (*n* = 40)	Old adults (*n* = 36)
BILATERAL MEASURES							
Mean values	***M (SD)***	***M (SD)***	***M (SD)***	***M (SD)***	**%Baseline** Mean	***M (SD)***	***M (SD)***
Step length	65.0 (6.1)	58.1 (9.1)	60.6 (9.6)	51.8 (9.3)	Step length	95.3 (4.5)	101.4 (3.3)
Gait speed	1.0 (0.2)	1.0 (0.2)	1.0 (0.2)	0.8 (0.3)	Gait speed	93.4 (8.2)	92.9 (9.1)
Step width	8.4 (2.4)	9.8 (2.4)	9.5 (2.8)	13.1 (3.2)	Step width	100.1 (22.7)	119.9 (100.3)
Stride length	132.3 (13.1)	118.5 (17.9)	NR	NR			
CoV (%)					CoV%		
Step length	5.4 (2.8)	7.1 (3.8)	8.3 (5.9)	15.7 (7.1)	Step length	104.8 (16.3)	127.5 (64.6)
Gait speed	6.4 (4.8)	6.9 (4.4)	9.4 (8.7)	21.6 (10.7)	Gait speed	106.1 (36.9)	153.7 (133.9)
Step width	81.8 (31.8)	71.8 (23.8)	81.9 (30.9)	85.2 (30.1)	Step width	101.0 (0.2)	101.0 (0.3)
Stride length	10.0 (9.0)	10.7 (12.1)	NR	NR			
LATERALIZED MEASURES							
Mean values	***M (SD)***	***M (SD)***	***M (SD)***	***M (SD)***	**%Baseline** Mean	***M (SD)***	***M (SD)***
Step length R	65.0 (6.5)	58.1 (9.6)	60.4 (10.1)	51.6 (9.4)	Step length R	94.8 (4.0)	99.0 (15.8)
Step length L	65.0 (85.8)	58.3 (8.7)	60.7 (9.2)	51.9 (9.4)	Step length L	95.8 (5.3)	101.3 (3.4)
Gait speed R	1.1 (0.1)	1.0 (0.3)	1.0 (1.0)	0.7 (0.2)	Gait speed R	93.4 (8.3)	94.8 (12.9)
Gait speed L	1.1 (0.2)	0.9 (0.2)	1.0 (0.2)	0.7 (0.2)	Gait speed L	93.2 (8.7)	93.0 (9.2)
Step width R	8.6 (2.5)	9.6 (4.2)	9.7 (2.7)	13.2 (3.3)	Step Width R	101.3 (28.5)	95.3 (141.4)
Step width L	8.1 (2.5)	9.5 (3.1)	9.3 (3.2)	13.1 (3.5)	Step Width L	101.6 (25.1)	126.0 (97.2)
Stride length R	132.1 (12.4)	118.8 (18.0)	NR	NR			
Stride length L	132.4 (14.0)	118.1 (18.1)	NR	NR			
CoV (%)					CoV (%)		
Step length R	4.7 (2.4)	6.8 (3.7)	6.9 (5.7)	13.9 (7.3)	Step length R	111.1 (26.6)	110.5 (41.4)
Step length L	5.4 (3.5)	6.8 (4.1)	7.7 (7.0)	13.5 (7.4)	Step length L	103.5 (25.1)	149.0 (98.3)
Gait speed R	6.6 (5.1)	6.7 (4.7)	9.2 (9.0)	21.6 (10.6)	Gait speed R	102.5 (17.2)	161.5 (171.1)
Gait speed L	6.4 (4.8)	7.1 (4.4)	9.4 (8.6)	21.3 (10.6)	Gait speed L	107.6 (48.2)	160.1 (124.6)
Step width R	73.8 (23.0)	65.6 (19.2)	77.1 (29.4	85.8 (33.9)	Step width R	101.0 (0.2)	101.0 (0.3)
Step width L	77.5 (32.0)	71.2 (25.1)	82.9 (35.5)	83.0 (26.5)	Step width L	101.0 (0.2)	101.0 (0.3)
Stride length R	9.2 (8.9)	11.2 (13.7)	NR	NR			
Stride length L	9.4 (10.9)	9.1 (9.6)	NR	NR			

Note. aMCI = amnestic Mild Cognitive Impairment; *M* = mean, *SD* = standard deviation; R = Right; L = Left; CoV = Coefficient of Variation; Step length (cm); Stride length (cm); Step width (cm); Gait speed (m/s). Nota bene: Results from Paper II are reported in % from Baseline

b) How does volitional control of attention to the right ear (Forced Right condition) affect gait?

Paper I

Bilateral results: The Old-old group walked slower, had shorter step length, and shorter stride length than the Young-old. Importantly, they had shorter strides and steps in FR compared to the NF condition. In addition, the Old-old had increased variability in step length during FR as compared to NF, see Table 7.

Lateralized results: A main effect of foot in stride length CoVs was seen after controlling for hearing status where right limb values were higher in both groups during the FR condition.

In this study we performed correlations between the DL conditions and gait parameters. Positive correlations were seen between right-ear answers and mean stride length and mean gait speed of the right foot, while positive associations existed between mean step length and mean gait speed, and the left foot in the FR-condition.

Paper II

Bilateral results: Volitional control of attention caused greater DTCs on speed and step length for both young adults and old adults. Bilateral data suggest that younger adults adjusted their step length mean more during FR compared to NF.

Lateralized results: When looking at the effects of focusing attention to the right ear, younger adults had larger DTC in their mean of step length variability, especially on the left foot, which indicated that younger adults had more adjustments of their step length variability on the left foot when attending right-ear stimuli in the FR condition. This caused the younger adults to walk slower, which may have caused more variability in their gait. This can be seen on the raw scores as depicted in Paper II's Supplementary Material.

A closer look to the percent change from Baseline showed that the older adults better preserved their mean step length than the younger group, especially in FR and FL. However, the older adults showed more perturbations in terms of increment of CoV in the directed attention-conditions while younger participants preserved almost the same step length variability across conditions. In addition, older adults showed an increment from Baseline to FR of 67.2% on gait speed variability, while the younger group preserved their gait speed variability across DL-conditions compared to Baseline, see Table 7. This showed that the older adults were more challenged by directing their attention to the right side. Still, younger adults experienced a unique *lateralized* effect on step length variability during FR.

Paper III

<u>Bilateral results</u>: The aMCI displayed shorter step lengths, slower gait speed, and wider step width than control group during FR-condition. In addition, step length variability and gait speed variability were larger in this group compared to controls.

<u>Lateralized results:</u> Higher variability on step length in the left limb was seen in both groups, especially during the FR condition, after controlling for hearing status. After controlling for hearing, asymmetries emerged in the control group, showing an increment in variability in their right foot and in their left foot in FR compared to NF. Also, step length variability in the right foot of healthy controls increased significantly during the FR-condition.

Table 7.

Overview of effects of FR on gait parameters in Paper I, Paper II and Paper III.

VOLITIONAL ATTENTION (FORCED RIGHT CONDITION)							
	Paper I		**Paper III**			**Paper II**	
	Young-old (*n* = 38)	Old-old (*n* = 40)	Controls (*n* = 52)	aMCI (*n* = 43)		Young adults (*n* = 40)	Old adults (*n* = 36)
BILATERAL MEASURES							
Mean values	***M (SD)***	***M (SD)***	***M (SD)***	***M (SD)***	**%Baseline** Mean	***M (SD)***	***M (SD)***
Step length	63.6 (6.2)	56.0 (9.3)	59.1(9.5)	50.9 (8.8)	Step length	94.2 (5.7)	99.9 (2.3)
Gait speed	1.1 (0.2)	0.9 (0.2)	0.9 (0.3)	0.7 (0.2)	Gait speed	90.4 (11.2)	90.7 (9.5)
Step width	8.3 (2.5)	10.3 (4.6)	10.0 (4.1)	13.1 (3.6)	Step width	100.2 (21.3)	116.9 (92.9)
Stride length	130.0 (13.5)	113.0 (19.0)	NR	NR			
CoV (%)					CoV%		
Step length	5.4 (3.8)	9.1 (5.6)	9.6 (7.0)	15.7 (7.2)	Step length	101.4 (16.6)	136.1 (79.0)
Gait speed	6.5 (7.7)	11.0 (14.7)	12.8 (15.5)	25.8 (29.7)	Gait speed	101.9 (21.8)	167.2 (194.1)
Step width	87.1 (33.6)	79.9 (29.9)	87.3 (29.7)	87.9 (29.5)	Step width	101.0 (0.3)	101.1 (0.5)
Stride length	10.0 (10.3)	9.4 (8.6)	NR	NR			
LATERALIZED MEASURES							
Mean values	***M (SD)***	***M (SD)***	***M (SD)***	***M (SD)***	**%Baseline** Mean	***M (SD)***	***M (SD)***
Step length R	63.4 (6.6)	55.6 (9.6)	58.7 (10.0)	50.4 (8.3)	Step length R	93.5 (5.9)	99.8 (2.6)
Step length L	63.8 (5.8)	56.3 (9.1)	59.2 (9.4)	50.3 (9.4)	Step length L	94.9 (5.9)	99.9 (2.4)
Gait speed R	1.1 (0.2)	0.9 (0.2)	0.9 (0.2)	0.7 (0.2)	Gait speed R	90.7 (11.1)	90.7 (9.6)
Gait speed L	1.1 (0.2)	0.9 (0.2)	0.9 (0.3)	0.7 (0.2)	Gait speed L	90.4 (11.4)	90.7 (9.5)
Step width R	8.6 (2.8)	10.5 (4.4)	10.3 (4.2)	13.2 (3.5)	Step Width R	102.3 (28.4)	102.6 (114.8)
Step width L	8.1 (2.2)	19.1 (4.9)	9.7 (4.2)	13.1 (4.0)	Step Width L	101.4 (27.4)	126.4 (98.9)
Stride length R	130.7 (14.4)	113.2(19.0)	NR	NR			
Stride length L	129.3 (12.9)	112.9 (19.1)	NR	NR			
CoV (%)					CoV (%)		
Step length R	5.2 (3.5)	8.6 (6.1)	7.9 (6.5)	16.6 (9.9)	Step length R	111.2 (29.5)	126.8 (74.7)
Step length L	5.2 (4.0)	8.7 (5.7)	7.9 (5.8)	17.0 (10.0)	Step length L	95.8 (21.1)	151.7 (101.5)
Gait speed R	6.3 (8.0)	10.4 (15.3)	12.4 (16.1)	26.5 (35.7)	Gait speed R	101.0 (16.11	162.2 (204.8)
Gait speed L	6.5 (7.7)	11.4 (14.6)	12.9 (15.2)	22.5 (35.8)	Gait speed L	102.2 (28.4)	177.7 (245.0)
Step width R	83.6 (31.4)	73.7 (29.3)	85.5 (29.9)	85.8 (29.8)	Step width R	101.0 (0.2)	101.1 (0.5)
Step width L	85.3 (35.6)	76.0 (26.8)	87.6 (31.8)	85.5 (29.8)	Step width L	101.0 (0.2)	101.2 (0.5)
Stride length R	10.8 (11.7)	10.0 (10.9)	NR	NR			
Stride length L	7.9 (9.4)	7.8 (6.1)	NR	NR			

Note. aMCI = amnestic Mild Cognitive Impairment; *M* = mean, *SD* = standard deviation; R = Right; L = Left; CoV = Coefficient of Variation; Step length (cm); Stride length (cm); Step width (cm); Gait speed (m/s). Nota bene: Results from Paper II are reported in % change from Baseline

c) How does volitional control of attention to the left ear (Forced Left condition) affect gait?

Paper I

Bilateral results**:** Bilateral results did not show differences between FR and FL on quantitative gait measures. Pearson's correlations revealed that right ear responses were negatively associated with left and right footstep length variability, and also left and right foot gait speed variability in FL. This means that when more right-ear answers were reported when focus of attention was towards the left ear the participants reduced their gait speed variability and step length variability.

Lateralized results**:** As in the bilateral data, similar outcomes in the FR-condition were also seen in the FL condition. Correlations between DL-responses and feet, showed significant positive associations were seen between right-ear responses in FL and mean step length, mean stride length, and mean gait speed on the right foot and left foot. Also, right-ear responses and variability of step length and variability of gait speed on the left foot and the right foot were negatively correlated.

Paper II

Bilateral results: The young adults walked the slowest and had shortest step lengths when attending to left-ear stimuli. On CoV, a main effect of Group for step length and gait speed was seen, showing that the older adults increased their variability of step length and gait speed mostly during FR and FL. In fact, older adults showed an increment from Baseline to FL in gait speed variability of 89.5%, while younger adults mainly showed same gait variability across all DL conditions, see Table 8.

Lateralized results: The DTC values per foot showed similar results as the bilateral results regarding gait speed. In step length, the younger group had larger costs than older adults. Based on percent of Baseline values, step length mean was shorter and gait speed mean was slower in younger adults, especially in FL. Regarding variability, some older adults had an increment in step length variability on their left foot also when attending left-ear stimuli.

Paper III

Bilateral results: In general, both groups exhibited shorter step length and wider step width from NF to the directed attention-conditions, However, mean and CoV values in step length and gait speed mean showed main effects of Condition and Group showing that the aMCI group walked slower and had shorter step length in FL condition compared to the control group.

Lateralized results: After controlling for hearing status, step length variability of the right foot increased significantly during FL compared to Baseline in cognitively healthy older adults.

Table 8.

Overview of effects of FL on gait parameters in Paper I, Paper II and Paper III.

VOLITIONAL ATTENTION (FORCED LEFT CONDITION)							
	Paper I		**Paper III**			**Paper II**	
	Young-old (*n* = 38)	Old-old (*n* = 40)	Controls (*n* = 52)	aMCI (*n* = 43)		Young adults (*n* = 40)	Old adults (*n* = 36)
BILATERAL MEASURES							
Mean values	***M (SD)***	***M (SD)***	***M (SD)***	***M (SD)***	**%Baseline** Mean	***M (SD)***	***M (SD)***
Step length	63.7 (6.0)	56.0 (9.3)	59.1 (9.6)	50.4 (9.1)	Step length	94.0 (5.8)	100.0 (0.0)
Gait speed	1.1 (0.2)	0.9 (0.2)	0.9 (0.3)	0.9 (0.3)	Gait speed	89.7 (11.2)	90.1 (8.7)
Step width	8.5 (2.4)	10.3 (3.9)	10.3 (3.7)	13.3 (3.7)	Step width	104.2 (24.4)	125.1 (103.7)
Stride length	130.0 (12.1)	113.6 (18.0)	NR	NR			
CoV (%)					CoV%		
Step length	5.4 (3.3)	8.4 (5.1)	8.9 (6.5)	15.8 (7.1)	Step length	104.2 (16.4)	136.5 (77.1)
Gait speed	6.4 (7.4)	9.5 (13.1)	11.9 (14.5)	26.6 (35.7)	Gait speed	100.6 (12.8)	189.5 (231.1)
Step width	82.4 (32.7)	79.3 (32.9)	87.1 (34.7)	85.2 (27.9)	Step width	101.0 (0.2)	101.0 (0.1)
Stride length	10.6 (8.9)	9.1 (8.7)	NR	NR			
LATERALIZED MEASURES							
Mean values	***M (SD)***	***M (SD)***	***M (SD)***	***M (SD)***	**%Baseline** Mean	***M (SD)***	***M (SD)***
Step length R	63.6 (6.0)	55.7 (9.7)	58.9 (9.9)	50.5 (8.9)	Step length R	93.8 (5.7)	100.0 (0.0)
Step length L	63.8 (6.0)	56.1 (9.1)	59.2 (9.4)	50.3 (9.4)	Step length L	94.3 (6.2)	100.0 (0.0)
Gait speed R	1.1 (0.2)	0.9 (0.2)	1.0 (0.3)	0.7 (0.2)	Gait speed R	90.1 (11.4)	90.1 (8.6)
Gait speed L	1.1 (0.2)	1.0 (0.2)	1.0 (0.3)	0.7 (0.2)	Gait speed L	89.4 (11.6)	90.1 (9.0)
Step width R	8.9 (2.7)	10.8 (3.7)	9.0 (4.0)	13.2 (3.8)	Step Width R	106.0 (33.9)	113.4 (127.3)
Step width L	8.1 (2.1)	9.9 (4.1)	10.6 (3.5)	13.5 (3.7)	Step Width L	105.8 (24.3)	130.7 (106.4)
Stride length R	130.3 (12.7)	113.8 (18.2)	NR	NR			
Stride length L	129.6 (12.0)	113.5 (17.8)	NR	NR			
CoV (%)					CoV (%)		
Step length R	5.2 (2.5)	8.0 (5.4)	9.4 (7.9)	15.5 (7.9)	Step length R	109.7 (24.1)	131.7 (74.2)
Step length L	5.3 (4.1)	8.2 (5.1)	9.4 (7.7)	15.1 (7.5)	Step length L	103.2 (25.8)	151.4 (95.9)
Gait speed R	6.4 (7.1)	9.8 (14.2)	11.9(15.1)	27.2 (42.9)	Gait speed R	100.2 (13.4)	208.7 (291.3)
Gait speed L	6.4 (7.7)	9.5 (13.1)	11.9 (14.7)	22.2 (11.6)	Gait speed L	100.7 (15.5)	193.4 (272.5)
Step width R	77.3 (29.3)	72.3 (28.1)	85.7 (35.4)	86.6 (32.7)	Step width R	101.0 (0.2)	101.0 (0.1)
Step width L	78.3 (28.6)	76.9 (29.0)	86.6 (32.7)	83.6 (2.5)	Step width L	101.0 (0.2)	101.0 (0.1)
Stride length R	10.8 (9.9)	8.8 (9.1)	NR	NR			
Stride length L	8.9 (8.9)	8.4 (8.4)	NR	NR			

Note. aMCI = amnestic Mild Cognitive Impairment; *M* = mean, *SD* = standard deviation; R = Right; L = Left; COV = Coefficient of Variation; Step length (cm); Stride length (cm); Step width (cm); Gait speed (m/s). Nota bene: Results from Paper II are reported in average % change from Baseline

8.3 Results of effects of dual-task paradigm on dichotic listening.

A summary of DL results of all papers is provided in this section.

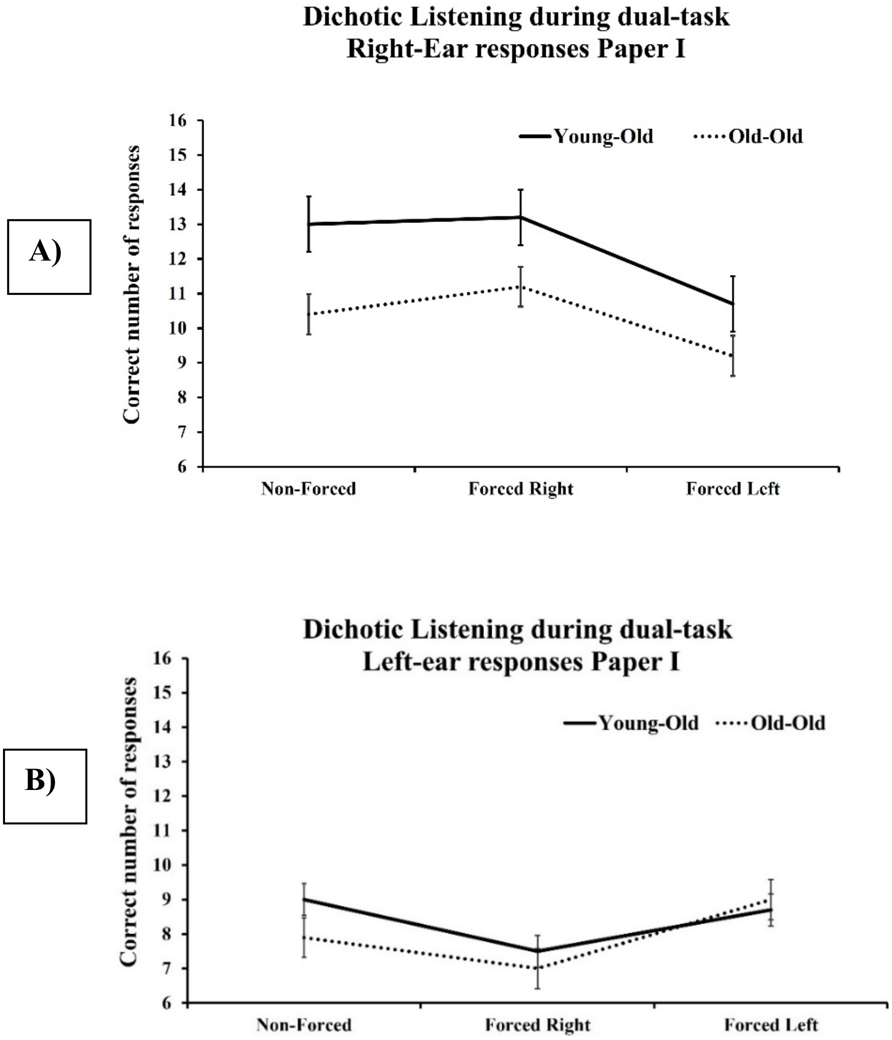
Paper I

Although both groups displayed a REA in all DL-conditions, the Young-old group reported more correct responses from the right side compared to the Old-old group across the DL conditions, see Figure 5. After controlling for hearing status, differences between laterality indexes were no longer significant. In addition, errors significantly still differed between the groups after controlling for hearing status. Omissions increased from NF proportionally to the FL condition, while in NF all errors were real errors. The Young-old displayed fewer real errors than the Old-old group.

A closer scrutiny to associations between gait and DL with the help of Pearson's correlations showed that right ear responses were mostly significantly associated with bilateral mean gait measures. Furthermore, right-ear reports were correlated negatively with CoVs in step length and gait speed., especially in FL. Left-ear responses were positively associated with bilateral CoVs of stride length in NF. In sum, higher number of correct answers from the right ear when instructed to attend the left ear decreased variability in speed and step length, while a higher number of left-ear responses in NF was linked to higher variability in stride length.

Figure 5.

Mean and SEM for correct responses from the right ear and the left ear across the three DL-conditions in Paper I.



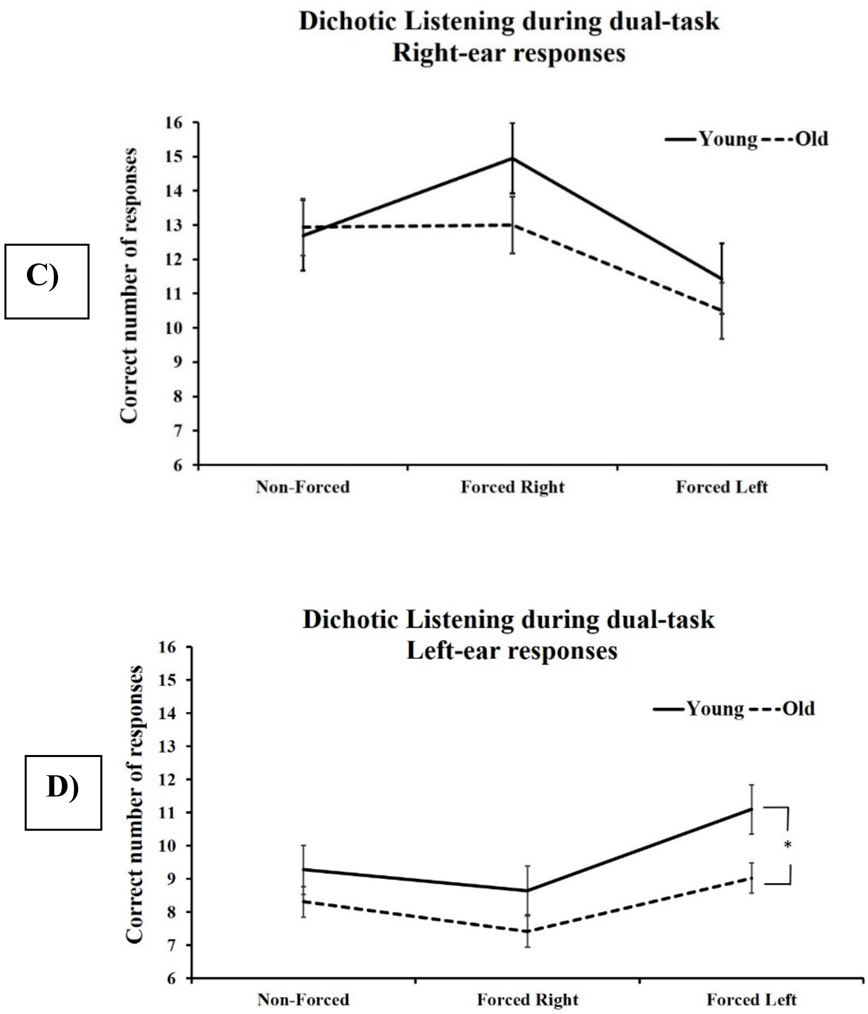
Note. SEM = Standard error of mean. Correct right-ear responses are displayed in A), and correct left-ear responses are displayed in B) across the three dichotic listening conditions in Paper I. Results displayed are after controlling for hearing status. Figure is novel for the purpose of this thesis and is a visualization of Table 4 in Paper I.

Paper II

As expected, a significant interaction between Condition and Ear was present due to the different attentional demands in the conditions. See Figure 6 for Also, an interaction effect between Condition x Group was seen in FL in left ear responses. The younger adults showed a REA in NF and FR, and a LEA in FL. The older adults showed a REA in all conditions. However, after controlling for hearing status, the interaction effect in NF was no longer present. The Old group did show a trend towards reporting less correct stimuli from the left side in FL.

Figure 6.

Mean and SEM for correct responses from the right ear and the left ear across three DL-conditions, as presented in Figure 1 and 2 in Paper II.



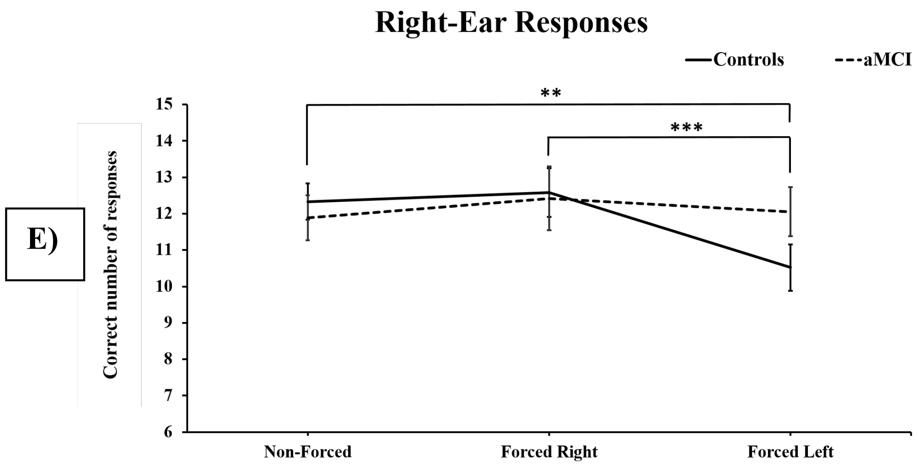
Note. SEM = Standard Error of Mean. Correct right-ear responses are displayed in C), and correct left-ear responses are displayed in D) across the three dichotic listening conditions. Results displayed are after controlling for hearing status; * $p = 0.05$

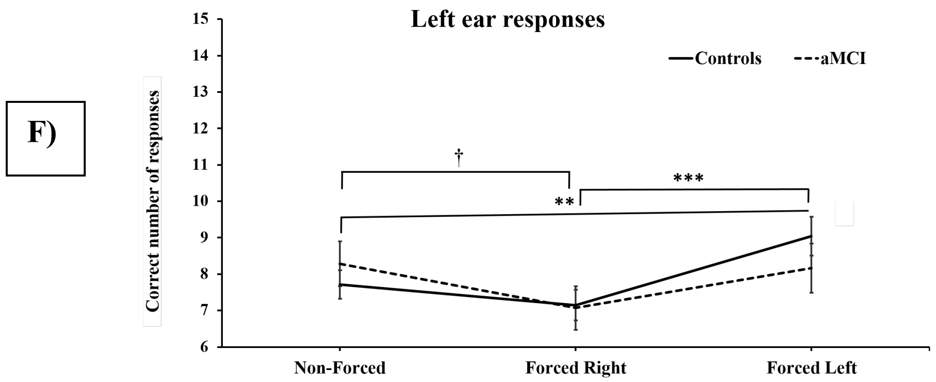
Paper III

The DL results showed that cognitively healthy older adults reported significantly less from the left side in NF compared to FR and FL, while aMCI reported more correct left-ear responses in NF than in FR, see Figure 7. Controls reported less from left-ear in FR. Though, after controlling for hearing, the results were not significant. A significant interaction effect on Laterality index showed that controls had a higher REA in FR (in addition to NF) compared to FL. However, after controlling for hearing status, this was no longer significant.

Figure 7.

Mean and SEM for correct responses from the right ear and the left ear across three dichotic listening conditions, as reported in Figure 2 and Figure 3 in Paper III.





Note. Correct right-ear responses are displayed in E). Correct left-ear responses are displayed in F). SEM = Standard error of mean; aMCI = amnestic Mild Cognitive Impairment; ** $p < 0.01$ and *** $p < 0.001$; The † denotes significant differences of $p < 0.05$ for aMCI group. Results displayed are after controlling for hearing status.

9 Discussion

9.1 Main findings of the thesis

This current doctoral work has introduced the application of dichotic listening (DL) during overground walking to the dual-task paradigm typically employed to understand the interplay between cognition and gait. The main goal was to answer how spontaneous attentional control vs. voluntary focus of attention to the right and left side affected gait parameters in older adults, healthy young adults, and older adults with amnestic MCI.

As a whole, DL as any other demanding attentional task, evoked several quantitative effects on gait. Importantly, we also obtained qualitative effects. However, due to a considerable variety of effects not always pointing to the same direction, the endeavor to summarize the effects across the different conditions and papers is challenging. Still, an effort to bring up the most salient effects to discussion follows.

<u>*Spontaneous attention and gait:*</u> We used the Bergen DL Test with three attentional conditions purportedly representing different difficulty levels. The first condition, in which spontaneous attention is assessed (NF-condition), has long been proposed to be an effortless situation for healthy individuals (Hugdahl et al., 2009). For this reason, we expected that by attending the most salient perceptual information, little changes would occur on gait outcomes. Nevertheless, we observed in Paper I and Paper II that the display of spontaneous attention is not as innocuous as it is supposed to be. In Paper I, the NF-condition evoked asymmetric effects on the mean gait speed of the Old-old group. We concluded that the NF-condition affects the Old-old participants negatively due to challenges in perceptual discrimination of the stimuli, which is most likely linked to age-related hearing loss. In Paper II, the same condition caused a bilateral increment in variability of step length (27% as compared to Baseline) and gait speed (53.7% as compared to Baseline) in healthy older adults as reflected by the percent of Baseline data. In this paper, the selected sample of healthy older adults had normal hearing. However, despite having “normal hearing,” older participants

already had higher hearing thresholds compared to younger participants as shown by the PTA comparisons (see Table 3, Paper II, page 6). Thus, for older adults, spontaneous attention while walking as measured in the NF-condition is a challenging situation simply due to reduced auditory perceptual ability, which causes uncertainty on attentional focus. Therefore, spontaneous attention during walking evoked gait speed asymmetries in cognitively healthy elders with mild levels of hearing loss (between 25 dB to 45 dB) and increased step length variability in healthy older persons with normal age-related hearing ≤25 dB Finally, in Paper III, we also observed a small significant asymmetry effect on step length variability in the aMCI group during the NF-condition, which arose only after controlling for hearing status. Even though, we concluded in Paper III that aMCIs basically did not show gait changes due to their inability to perform the DL task. It is evident that the challenges these aMCI participants experienced rely on their ability to focus their attention to one specific ear, not due to reaction to auditory stimuli. Even if they presented with more pronounced hearing loss than healthy controls, they still showed spontaneous attentional responses.

Lateralized attentional control and gait: The **FR-condition** in DL supposedly entitles a moderate difficulty level for healthy right-handed persons. Here, subjects are required to volitionally focus their attention to the right ear, which is in fact what right-handers usually do, in line with REA. However, the increment in difficulty level as compared to the NF-condition relies on the need to inhibit competing stimuli coming from the left ear. During this condition in Paper II, we found significant increments on stride length variability of both older groups and in step length variability of the Old-old group. However, several of the obtained effects were moderated by hearing status (see next section about the role of hearing, page 75). Notwithstanding, in Paper II we found the most important effect of this condition in the group of healthy young adults. The main finding of Paper II was the obtention of an asymmetric effect on the variability of step length as reflected by dual task costs. It turned out in this specific study, that the dual-task environment created by the DL in the Optogait arena was challenging for healthy participants who normally walk at a higher pace than healthy older persons. Thus, when confronted to execute DL at the same time to walking in rounds, the younger participants (who all were right-handed) had to adjust their performance by decreasing their speed and reducing their left footstep length variability, while they correctly executed the FR-condition (i.e., reported correctly right-ear stimuli and displayed a high REA). In other words, in order to properly report right-ear stimuli while walking, they had to regulate their gait differently and presented an asymmetric step length variability. In contrast, the same condition in the healthy senior group did not evoke any important change on the raw scores of gait outcomes, but all DL conditions, especially the FR and FL-conditions, affected the *variability* of all gait outcomes in these participants. In sum, volitional focus to the right ear exerts negative effects on the gait of healthy older adults as their variability increases, and thus, also the risk of falls. Unsurprisingly, the same results were obtained in Paper III in the healthy control group. As for the aMCI, we cannot conclude whether or how volitional focus of attention affects the gait of these participants since the level of difficulty surpassed their capacities as the aMCI individuals did not show changes in REA across the DL-conditions. Most likely, we need to implement an easier version of DL to reach conclusions on this specific population.

Finally, the **FL-condition** indeed represented the most difficult condition for healthy subjects. This is particularly evident in Paper I. In this study, focusing to the left-side caused strong increment of gait variability in the Old-old group, as displayed in the correlational data. Interestingly, it also was demonstrated that older persons by responding to right-ear stimuli in any of the forced DL-conditions (including FL-condition), their gait variability decreased. In other words, the risk of falls diminished. In contrast, when the older participants responded to left-ear information during dual-tasking, their gait variability increased. In line with these findings, Paper II also showed that the younger adults and healthy older group increased their step gait variability in the FL-condition. Paper III did not reveal any new data, in fact in this last paper the older control group showed similar gait effects when executing both forced attention-conditions, suggesting that lateralized volitional control to any ear indeed exert greater perturbations on gait.

9.2 The moderating role of hearing status

The second aim of this present thesis was to evaluate whether hearing status moderated the gait changes caused by DL. In the previous section it has been already discussed that good perceptual acuity is important and affects gait parameters during spontaneous verbal attention. Therefore, the NF condition cannot be regarded as an easy situation for cognitively healthy older adults. Through all three papers, and especially in those contrasting only older samples (Paper I and III), the effects of hearing appeared as they were particularly controlled for. Notwithstanding, even if we have obtained indication about the importance of hearing status on the gait-cognition association, it is important to stress the difficulty to really unveil the extent and real role of hearing loss. The reason is, as exposed in Paper I, that hearing loss co-exist with cognitive decline and is tightly related to increasing age. Thus, we cannot exactly conclude how hearing loss affects the gait-cognition relationship from the findings of the present studies. What we can assert, is that this factor is of importance as a comorbidity element in the "gait, cognition, and sensory loss- triad".

In general, little attention has been devoted to the role of hearing loss and gait perturbations. However, a link between hearing loss and poor mobility has become more established in recent years (Martinez-Amezcua et al., 2021; Viljanen et al., 2009). Also, previous work has showed that decline in auditory function contribute to age-related difficulties in cognitive functions (Lin & Ferrucci, 2012; Schneider et al., 2010). A possible explanation for the association between hearing decline and mobility decline is the competition for cognitive capacity that is necessary to support both auditory and motor processes in aging, especially when performing several activities simultaneously. Also, hearing loss imposes increased listening effort and hence creates an increased need for attention allocation (Nieborowska et al., 2019). Therefore, auditory and motor processes may compete for a limited pool of shared cognitive resources to compensate for decline in these domains (Bruce et al., 2017), which in turn contributes to performance trade-offs in the association between age-related declines in hearing and mobility. Nevertheless, few dual-task studies have been carried out to explore the interrelationship between decline in auditory and mobility functions in aging under realistic, everyday conditions with detailed assessments of both cognition, hearing, and gait.

Older adults with hearing impairments exhibit greater dual-task changes in the concomitant cognitive task and in gait, showing that extra effort at the sensory–perceptual level due to hearing loss has negative consequences to motor tasks and is further magnified with increased age (Bruce et al., 2017; Carr et al., 2020; Huang et al., 2019). One explanation to this connection has been the cognitive compensation hypothesis, which suggests that older adults compensate for hearing loss and declines in mobility by recruiting competing higher order cognitive resources as compensation. This recruitment becomes more evident in challenging multi-tasking conditions (Li & Lindenberger, 2002).

In our work, the various cognitive demands by DL disturb both gait variability and induce asymmetry in gait, which are both associated with dysfunction in executive functioning (Montero-Odasso & Camicioli, 2020). In all papers in this thesis, older adult groups showed worse results on neuropsychological tests compared to the younger and healthier study groups (i.e., Young-old in Paper I, young adults in Paper II, and cognitively healthy older adults in Paper III). In Paper III, even the aMCI group showed significantly worse results on tests on EF, regardless of their condition being mainly associated with memory decline. DL performance is dependent on executive control in addition to adequate hearing, and impairment in these domains may together severely tax attention resources in a dual-task setting. Hearing loss demands more allocation of cognitive resources. The results can therefore point to a possible overloading of common brain areas necessary to perform both attentional focus and inhibiting processes, and walking, i.e., frontal lobe circuits. Furthermore, processes employed by both tasks in this dual-task setting may share neurobiological correlates in the brain causing older adults with hearing loss to demonstrate more compensatory neural responses to challenging walking conditions to maintain mobility (Park & Reuter-Lorenz, 2009). For example, Carr et al. (2020) showed that older adults with hearing impairments exhibit greater changes on both the cognitive task and gait outcomes. These data demonstrate that losses at the sensory–perceptual level, in this case related to hearing, have negative consequences for older adults (Carr et al., 2020). Although the DL results were secondary to this investigation, it is worth noting that laterality may be of importance in this overloading of cognitive resources. We expected less laterality (i.e., REA) in the older groups than younger groups and a tendency was present, however, and somewhat surprising, the aMCI group did not show a laterality effect. This may also point to difficulties with conducting this DL task due to executive dysfunctions and not only to hearing impairment.

It is also plausible that callosal integrity and its connectivity to frontal wiring is of importance behind these gait asymmetries as the degeneration of corpus callosum is central in DL performance, but also of importance for gait as it may impair mobility indirectly (Bolandzadeh et al., 2014; Bruijn et al., 2014; Koo et al., 2012). Although we did not investigate brain correlates in this work, our group has demonstrated that the present data has a strong relationship with age-related deteriorations of frontal circuitry and the corpus callosum (Castro-Chavira et al., 2019). Future neuroimaging studies need to pursue this line of research and complement the understanding of the mechanisms in this dual-task context by conducting additional research of other neutral components, such as cortical thickness or grey matter integrity.

In sum, the interplay of these three aspects of aging: hearing loss, cognitive impairment and gait disturbances has been found to be related, but *in what way* has yet to be explored. The application of DL with walking overground has proved to be a fruitful approach in this matter. Accordingly, by enhancing for instance peripheral auditory function or by providing better hearing aid at an early stage of hearing decline in older adults may enhance cognitive functioning, and thus, improvements in gait may occur.

9.3 The gait environment of the present dual-task paradigm

Some closing remarks need to be stated in relationship with the gait context. Our data clearly demonstrated that by introducing the OptoGait arena to allow for continuous execution of DL, a certain degree of difficulty is added for both younger and older groups.

Although, the method applied in the three papers was the same, the calculation of effects of the dual-task were slightly different. In Paper II, we applied the relative difference from Baseline to the various DL-conditions in addition to percent change from Baseline, while in Paper I and Paper III we explored results in raw scores. The approach in Paper II was chosen due to peculiar results displayed by the young group who performed *worse* than the older adults on all raw gait parameters, i.e., shorter step lengths, stride lengths, wider step widths, and more variability, regardless of conditions, which can be scrutinized in the Supplementary Tables to Paper II. We believe that such a new environment created by our dual-task paradigm posed different challenges to the different populations we studied. Thus, we cannot minimize the importance of the walking environment and other conditions to perform DL while walking need to be further explored. In the past, it has been postulated that gait measures in daily life differ from in-lab dual-tasking. For instance, in most dual-tasks studies, participants are required to walk for shorter distances in a linear fashion on a walkway. Recent studies have shown that cognition have more significant associations with real-life mobility, especially attention, which is in accordance with the view that more complex activities require more complex cognitive contributions (Giannouli et al., 2018). If walking is a natural manifestation of executive functioning and attention, then manipulating factors in the environment for locomotor adaptation will further tax executive functioning. In our experimental situation, subjects needed to walk straight as well as to negotiate the turns to follow the path within the walking area and adjusting walking accordingly. Consequently, the design of the present study was intended to be as ecologically valid as possible, allowing subjects to walk as in real life, e.g., continuously, overground, including turning, and thereby we were able to obtain transferable gait measurements from this design. In the future, to complement this current dual-task paradigm, applying for instance portable insoles while walking in open space areas, could provide more insight into the current dual-task context involving dichotic listening.

9.4 Limitations and strengths

The current work is not without limitations. First, we acknowledge the lack of performing DL as a single-task. Central to the ecological approach, is that dual task costs/changes should be investigated in both task domains to understand the trade-offs between motor and cognitive functioning. However, because we wished to evaluate the effects of the experimental situation without previous exposure to DL, we intentionally did not assess DL as a single task, a similar approach seen in several studies that also has not assessed single-task performances in cognition (See Al-Yahya et al., 2011). Furthermore, the rationale of avoiding single-execution of DL in this current work was important to evaluate the effects of this overground dual-task paradigm as a novel situation where participants were naïve to the cognitive task. We considered this to be a more ecological approach. An additional issue under consideration was that we wished to reduce test fatigue and potential practice effects. The methodology utilized in this current work has not been applied before and is exploratory in nature. However, future replications should include DL as a single-task to answer how experience affect performance in our dual-task paradigm.

Another potential limitation may be the lack of instruction about task priority in the dual-task experiment. In the absence of specific instructions about which task needs to be prioritized, subjects tend to allocate attention to their gait at the expense of the cognitive test, which is a "posture-first" strategy (Shumway-Cook et al., 1997). In our study, the instructions were to perform the DL task and walking simultaneously as well as possible, which implied an equal prioritization. Nevertheless, each single participant might have prioritized differently. Some dual-task experiments ask subjects to focus and prioritize one task over the other. This manipulation of task prioritization provides knowledge about age-related changes under specific requirements and will certainly provide complementary information to the present research. Future studies applying this current dual-task paradigm should be carried out to control for the effects of task prioritization in different populations of older adults.

As already mentioned, the environment in which the dual task experiment was performed may have posed different challenges to different populations of older adults. Future studies are encouraged to apply other walking protocols to evaluate whether the present findings rely on the sole use of DL or whether gait alterations due to DL are tightly related to the experimental situation.

This current thesis has also strengths. Besides the innovative aspect of the present investigation, we believe that the different studies have additional strengths. One of these is application of a thorough neuropsychological evaluation to all participants in this study. This provides with more accurate cognitive profiles of both healthy subjects but also of the MCI individuals. A significant strength concerns the sample of MCI individuals recruited for Paper III who were referred from the local university hospital. These individuals were thoroughly assessed upon recruitment and thanks to the completes cognitive assessment they were accurately subtyped. Many studies recruit both healthy controls and MCI individuals from samples of community-dwelling older adults and participants are only screened with simple cognitive tests (Lowe et al., 2020). In contrast, our study is based upon a thorough neuropsychological assessment. Moreover, by including several neuropsychological tests, especially those measuring executive functions and attention, we acquire crucial diagnostic information relevant to the risk assessment of falls in older adults. Such cognitive information is likewise important and complementary in the study of falls and sensory loss. Hence, our studies suggest inclusion of thorough neuropsychological evaluations in relationship to dual-task assessments. The opposite is also true, as dual-task assessment can be included in neuropsychological assessment to improve the differential diagnosis of cognitive impairment in aging (Lowe et al., 2020; McFadyen et al., 2017).

Finally, our dual-task approach proves the importance of considering dysfunction in different body systems to better understand of age-related cognitive-motor dual-task effects in older adults.

Application of DL to the study of gait-cognition-hearing-loss triad

An important aspect about dual-task studies is that they should employ laboratory-tasks that closely resemble real-world scenarios (Li et al., 2005). The challenges with previous studies, is that they have used cognitive tasks that are very diffuse in terms of the exact cognitive abilities measured, sensorial modality, ecological validity, and understanding of brain correlates. Therefore, we have proposed dichotic listening as a very advantageous tool to implement in dual-tasking for gait, as we have good understanding of the mentioned points (attentional mechanisms assessed, sensorial modality, and neural correlates). Moreover, it resembles a daily act of talking and listening while walking. Thus, our findings suggest that this dual-task paradigm is more ecological valid approach to study the interplay of gait, cognition, and sensory loss in comparison to previous dual-task paradigms.

This is the first attempt to combine a robust instrument like DL into dual-task methodology involving walking on different age groups. The present work unveils that different attentional demands impact walking differently in various study populations. Gait is affected regardless of what cognitive task is performed simultaneously to walking. Still, the pattern of dual-task changes depends on the type of cognitive task being performed while walking (Beauchet et al., 2005). It is critical to understand *how* different cognitive demands cause deteriorations in gait. Varying demands of the cognitive task within the same sensorial modality in dual-task context may be the key to assert the mechanisms related to the interplay between cognition and gait.

9.5 Clinical implications

The clinical disciplines of physiotherapy and medicine have been dominating in the study of gait and cognition, and risk of falls. We believe that the field of psychology can also to be an important contributor in the understanding of gait disturbances in aging. This current work stresses the importance of a more holistic approach in the assessment of cognition and mobility in older adults, which demonstrates how dual-task approaches may function complementary to a cognitive assessment.

The present findings suggest that due to the associations between mobility, cognition, and hearing, clinicians must embrace an interdisciplinary assessment of older adults involving these domains. Applying DL to overground walking may provide a cost-efficient and sensitive measure for the detection of gait difficulties, in addition to cognitive and auditory dysfunction. Furthermore, when assessing cognitive status, it is crucial for clinicians to consider the impact of hearing loss on the test results and cognitive impairment. Given that a substantial number of older adults have untreated hearing loss, targeted audiological screening to complement cognitive and mobility assessment and rehabilitation may prove beneficial. Such a holistic approach may be particularly beneficial to aid activities of daily living and help maintaining functional independence in older adults. For instance, for older adults it would be beneficial to reduce the amount of multitasking when walking or when providing important information. Lastly, this paradigm points to the importance of an interdisciplinary and targeted rehabilitation approach in older adults including audiological, cognitive and mobility interventions. Future studies will need to utilize DL and overground walking within rehabilitation.

9.6 Conclusions

The main finding of this doctoral work is that the application of a cognitive task assessing lateralized attention indeed induces lateralized gait perturbations in healthy older adults, young adults, and possibly to a lesser extent in older adults with amnestic MCI. Our observations do support the findings of previous literature in the notion that the more complex the secondary task, the greater the impact there is on the spatiotemporal parameters of gait in a dual-task context. However, DL causes variability and asymmetric effects in healthy populations. Gait was more perturbated from single-task to dual-task, and when attending the left side, simultaneously ignoring the right side. Also, listening to the right-side stabilized walking in older adults. In addition, hearing loss was a modulating factor causing asymmetry as a compensation strategy in healthy populations, but not in cognitively impaired participants. Applying a cognitive task that manipulates attention experimentally in defined ways under the same sensory modality while walking overground, provides a strong and more ecologically valid situation resembling everyday life settings than previous dual-task studies.

These findings contribute to the understanding of the mechanisms of the interplay between cognition and gait, and how hearing loss contributes to this interrelationship and their importance for risk of falls. However, hearing, mobility, and cognition have typically been assessed independently of each other. These findings point to that sensory, motor, and cognitive deficits arise together in aging and jointly affect the ability to successfully participate in activities of every life, such as walking and communication. The utilization of DL while walking overground is a fruitful way to investigate these mutual associations, especially in older populations. This may also constitute a promising approach for the improvement of diagnosis, prevention, management of falls or cognitive impairment and to better tailor holistic interventions to preclude further functional deterioration.

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Paper I

Gorecka, M.M., Vasylenko, O., Espenes, J., Waterloo, K., & Rodríguez-Aranda, C. (2018). The impact of age-related hearing loss and lateralized auditory attention on spatiotemporal parameters of gait during dual-tasking among community dwelling older adults. *Experimental Gerontology,* 111, 253-262. Doi: 10.1016/j.exger.2018.07.015

Experimental Gerontology 111 (2018) 253–262

Contents lists available at ScienceDirect

Experimental Gerontology

journal homepage: www.elsevier.com/locate/expgero

The impact of age-related hearing loss and lateralized auditory attention on spatiotemporal parameters of gait during dual-tasking among community dwelling older adults

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ARTICLE INFO

Section Editor: T Foster

Keywords:
Hearing loss
Dichotic listening
Healthy aging
Cognitive decline
Walking overground

ABSTRACT

This investigation assessed the impact of hearing loss and lateralized auditory attention on spatiotemporal parameters of gait during overground dual-tasking by the use of the dichotic listening task. Seventy-eight right-handed, healthy older adults between 60 and 88 years were assigned to a Young-Old (< 70 years) or an Old-Old (> 71 years) group. Cognitive assessment and pure tone audiometry were conducted. Spatiotemporal parameters of gait quantified by mean (*M*), and coefficient of variations (CoV) were evaluated with the OptoGait system during 3 dichotic listening conditions: Non-Forced, Forced-Right and Forced-Left. Factorial analyses of variance and covariance were used to assess group differences and the moderating effects of hearing status, respectively. Results demonstrated that three of the gait parameters assessed were affected asymmetrically by the dual-task paradigm after controlling for hearing status. Asymmetries existed on step width, gait speed and variability of stride length. Finally, correlations between gait outcomes and dichotic listening results showed that *M* and CoVs in gait parameters during right-ear responses were longer compared with left-ear. Left-ear responses were related to increased variability on stride length, which indicates higher difficulty level. Hearing status varying from normal to mild levels of hearing loss modulates spatiotemporal gait outcomes measured during dichotic listening execution. Findings suggest that attending to left side stimuli relates to increased gait variability, while focusing on right-side assures a safe walk. Results demonstrated that attending to right-ear stimuli is an adaptive strategy for older adults that compensates for limited sensorimotor and cognitive resources during walking.

1. Introduction

The "dual-task paradigm" has been broadly employed to study aging effects on multitasking, and more specifically, on the interplay of gait and cognition. This paradigm is used to disentangle the possible causes of falls in older populations. Notwithstanding, there are some caveats. One is the absence of appropriate rationale for the selection of the cognitive tasks challenging gait. Since type of cognitive task used during walking matters (Beauchet et al., 2005), tests measuring specific cognitive mechanisms that can be naturally adapted on dual-tasking should be prioritized. A second limitation is the lack of information about the role of sensory loss influencing the gait-cognition association. To our knowledge, the very common condition of age-related hearing loss among older adults over 60 years has not yet been explored in dual-task investigations.

Age-related hearing loss (ARHL) or presbycusis is a chronic, degenerative condition following accumulating extrinsic and intrinsic factors resulting in impairments in cochlear transduction of acoustic signals (Huang and Tang, 2010). ARHL is also one of the most prevalent chronic conditions in the older population (Yamasoba et al., 2013). As it is well established, ARHL aggravates with increasing age and it goes hand by hand with declined cognition (Lin et al., 2011a). It is calculated that 37% of older persons between 60 and 70 years have a hearing loss over 25 dB, while the proportion elevates to 60% among those over 70 years (Van Eyken et al., 2007). Whether ARHL and cognitive decline arise due to a common etiology or as a result of a direct link between the two phenomena (Wayne and Johnsrude, 2015) is still a matter of debate. Nonetheless, hearing loss and cognitive deficits co-exist in the older adult and both conditions have been associated with impaired

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https://doi.org/10.1016/j.exger.2018.07.015
Received 1 February 2018; Received in revised form 23 July 2018; Accepted 23 July 2018
Available online 27 July 2018
0531-5565/

functional status (Chen et al., 2015) and increased risk of falls (Lopez et al., 2011). To our knowledge, there are only two earlier studies addressing the issue of hearing loss and dual-tasking (Lau et al., 2016; Bruce et al., 2017).

Because hearing loss is closely connected to cognitive decline in aging and it also affects walking and balance (Lin et al., 2011b) it is important to take the condition into account in dual-task studies. A central interest is to understand the relevance of sensorimotor changes due to aging when walking, listening and talking occur concurrently. In fact, such a scenario has been addressed under experimental conditions using the dichotic listening test (DL) (Decker et al., 2013; Decker et al., 2017). DL is a robust task for the study of divided attention and executive function in which participants need to attend to specific auditory information during trials where competing stimuli are simultaneously applied to both ears. During three conditions subjects are required to report information based on a self-selected choice or from one specific ear. DL tests hemispheric lateralization of language and the fact that the brain mechanisms underlying DL performance are well-known is of great interest for dual-task research. The benefit of the test is its ability to assess attention across different levels of task difficulty as well as possible asymmetrical effects on gait due to lateralized focus of attention.

1.1. Why does lateralized focus of auditory attention influence gait asymmetrically?

In order to answer this question, we need to address the topic of hemispheric specialization in aging and specifically in DL and gait. With increasing age, hemispheric specialization tends to diminish as observed in functional imaging studies (Cabeza, 2002). However, hemispheric specialization is differently affected by age depending on the cognitive modality or function under consideration. For instance, during performance of the DL test, right-handed older adults demonstrate larger difficulties to report stimuli from left-ear while their ability to report from right ear is more accentuated (Stecker et al., 2015). The preference for right-ear stimuli is a phenomenon called “the right ear advantage”, which exists in all right-handed subjects and is explained by the left-hemispheric dominance for language processing (Hugdahl, 1988). In contrast, processing of left-ear stimuli is more challenging as information coming from left-ear is transmitted via the anatomical decussation of fiber pathways to the right hemisphere. There, the signal has to be further transferred through corpus callosum to the left hemisphere for final processing (Hugdahl et al., 2008). Thus, the difficulty to report stimuli from left-ear in aging is thought to be caused by decreased inter-hemispheric transfer of the auditory input, probably due to size reduction of the corpus callosum (Westerhausen et al., 2015).

Concerning the effects of aging on lateralized organization of motor functions, findings depend on the action in question. For example, in upper-limb function preservation of lateralized capacities has been documented (Sebastjan et al., 2017). As for walking, the situation is quite different. In healthy individuals gait is a rather symmetric function (Viteckova et al., 2018), controlled by basic spinal motor programs that keep movement synchronization (Ivanenko et al., 2006). However, under specific contexts like in dual-tasking, the nervous system needs to integrate additional sensorimotor information by utilizing higher-level cortical functions and volitional actions. These events perturb central generator patterns for locomotion (Ivanenko et al., 2006; Robinson and Kiely, 2017). In aging, walking becomes a more demanding action and more involvement of executive functions and attention is required (Yogev-Seligmann et al., 2008). Thus, additional cognitive loading in dual-tasking further disturbs gait patterns.

In the past, few studies have evaluated the effects of the concomitant cognitive task on gait asymmetries in healthy older adults, probably because asymmetries are regarded as a pathological feature (Yogev et al., 2007). One of these studies evaluated gait asymmetries by the use of a verbal fluency test (Dalton et al., 2016), but data only showed a trend towards disrupted asymmetry. In another recent investigation, arm swing asymmetries in healthy older adults have been reported during execution of a dual-task employing the Stroop test (Killeen et al., 2017). Authors of this study remark the absence of information about asymmetric effects for lower limbs, implying that gait asymmetries might not arouse by dual-tasking in healthy populations. However, this is still an open question as for now, most of the cognitive tests adopted in dual-task research do not deliberately assess lateralized cognitive functions. Therefore, in the present study we used the DL test, which increases cognitive load in a lateralized way. Since DL performance recruits higher attentional resources on one brain hemisphere (Tervaniemi and Hugdahl, 2003), a lateralized cortical activation during DL is superimposed to motor programmes acting on both sides of the corticospinal pathway that control both sides of the body. Hence, it is reasonable to expect that lateralized focus of attention will disrupt coordination of these motor programmes asymmetrically.

1.2. Interest of the present study

The use of DL as a secondary task has only been investigated during walking on a treadmill (Decker et al., 2013; Decker et al., 2017). Because it is well documented that walking on a treadmill modifies the way in which participants ambulate (Hollman et al., 2016), findings from these studies cannot generalize to normal walking, it is necessary to assess DL in dual-tasking during overground walking. In addition, gait studies using treadmills augment the attentional requirements as achievement of a steady walk on the device increases the cognitive load and subjects tend to prioritize walking at the expense of the secondary task (Regnaux et al., 2006). This means that the effects exerted by DL need to be investigated on regular walking, especially concerning older adults for whom just walking already demands increased cognitive control (Yogev-Seligmann et al., 2008). For these reasons, it is important to evaluate DL as a secondary task during walking overground, which will bring an optimal ecological valid environment that resembles daily situations. Therefore, the aim of the present study was two-fold: First, evaluate possible asymmetric effects of DL in a dual-task paradigm during walking overground in right-handed healthy older adults and secondly, to assess the moderating effects of hearing loss on this experimental situation.

2. Method

2.1. Participants

Seventy-eight right-handed volunteers ranging in age between 60 and 88 years ($M = 71.1$, $SD = 6.6$) participated in the dual-task study. All the participants were involved in a larger umbrella project of motor functions and cognition at our institution. Only right-handed individuals were enrolled as it is demonstrated that left-handed people present atypical lateralization patterns (Westerhausen et al., 2015). Because specific age ranges of older adults may have an impact on study results (e.g., Ihle et al., 2016), participants were assigned to a Young-Old group (YO, ≤70, n = 38) or to an Old-Old group (OO, ≥71, n = 40). This approach has been adopted by numerous investigations, and it assures inclusion of specific age-ranges of older adults with different levels of hearing loss and cognitive deficits. Educational level of the whole group was 13 years on average ($SD = 3.9$), 72% of the participants were retired and 56% were females. All individuals were community living older adults from north-Norway, free of major diseases or cognitive troubles. Inclusion criteria were being right-handed, native Norwegian speaker, above the age of 60, no diagnosis of orthopaedic, motor or other co-morbidities likely to impact gait and cut-off criteria on MMSE > 27 to assure normal cognitive status (Petersen et al., 1999). Exclusion criteria were having a diagnosis of pathology that directly affects the musculoskeletal system, recent surgery, acute illness, or cardiac/movement disorders. Participants were also screened for depression with the Beck Depression Inventory II (Beck et al., 1996) and none of the participants scored within the depression range. Exclusion criteria to avoid high-moderate to severe impaired hearing which may hampering DL execution included averaged pure-tone threshold higher than 45 dB on any ear and interaural asymmetry between ears of not > 15 dB, which is the clinical definition for asymmetric sensorineural hearing loss (Saliba et al., 2009). The latter criterion is crucial in the present study due to the interest in evaluating lateralized auditory stimuli in healthy participants. It should be reminded that ARHL is a gradual process affecting both ears in parallel and that any asymmetric impairment suggest the existence of damage to the auditory system beyond normal effects of aging (Howarth and Shone, 2006).

Recruitment of participants was conducted through advertisements at the local senior citizens' center, flyers, and by means of word of mouth. Informed consent was obtained from all participants and they were aware that they could leave the study at any time if they so choose. The study was approved by the Regional Research Ethics Committee.

2.2. Measures

2.2.1. Audiometric screening and group assignment

A pure tone audiometry was conducted in all participants for frequencies: 0.25, 0.5, 1, 2, 4 and 8 kHz with a screening audiometer MADSEN Itera II. The average hearing sensitivity reflected by "pure tone averages" (PTA) of the frequencies 0.5, 1, 2 and 4 kHz was calculated for each ear. A score equal to or > 25 dB (dB) on PTAs was used to classify those with impaired hearing, while a score equal to or < 24 dB on PTAs was the cut-off to classify those with normal hearing (WorldHealthOrganization, 2017). We based group division on worst-PTA, which is the highest threshold presented from the two ears. We employed worst-PTA since this calculation identifies individuals with heavily hearing dysfunction that may affect gait and auditory performance.

2.2.2. Gait assessment and apparatus

Spatio-temporal parameters of gait were acquired during walking in single (only walking) and dual-task situations with the OptoGait photoelectric cell device (Microgate, Bolzano, Italy), which has proved to be a highly reliable and valid instrument (Bernal et al., 2016). Description of this system has been reported elsewhere (Lienhard et al., 2013). Means and coefficient of variations for gait speed, step length, step width and stride length were calculated and used in statistical analyses. We selected these parameters as they represent the "pace" aspect of the gait cycle (Verghese et al., 2007; Hollman et al., 2011), which is controlled by subcortical and cortical areas while other gait features such as rhythm (i.e., cadence and various timing measures) are regulated by spinal and brainstem mechanisms (Verghese et al., 2007). For this reason, "pace" parameters have proved to be more sensitive to reduced executive functioning. Gait data were evaluated statistically for both limbs (i.e., average scores calculated by taking together the right and left side data) and for each separate limb to explore lateralized effects of the dual-task. The OptoGait device was placed in a quiet room creating an area of 7 m. long × 1.3 m width in which subjects were asked to walk in rounds at a self-selected comfortable speed. Participants were instructed to use flat shoes with heel not exceeding 3 cm (Kressig and Beauchet, 2006).

2.2.3. Dichotic listening (DL) task

The Bergen dichotic listening paradigm adapted to be presented via the *E*-Prime software was used. Detailed explanation of the test has been previously reported (Andersson et al., 2008). Shortly, two of six possible syllables (BA, DA, GA, KA, PA, TA) are presented dichotically through noise-cancelling headphones in three different conditions of 3 min. each. There are 30 possible combinations of all syllables and 6 trials presenting the same syllables (homonyms). All stimuli were presented in a randomized order at a duration of 450–500 ms. with a 500 ms. intertrial interval and with three randomizations for each attentional instruction. The first condition (Non-forced), requires participants to report the clearest perceived sound, which indicates side preference of attention (right vs. left ear advantage). Because this is a free choice situation, the NF condition is always presented first. Thereafter, the second and third conditions are presented counterbalanced, depending on the participant's identification number. Subjects assigned with even identification numbers underwent the Forced-Right condition first and subjects with uneven identification numbers received the Forced-Left first. One of these conditions requires participants to report stimuli presented only to the right-ear (Forced-Right condition), while the other requires to report stimuli from left-ear (Forced-Left condition). Competing stimuli from the opposite ear has to be ignored. Scored outcomes reflect correct matched answers for each ear, homonyms, errors and non-responses by condition. Following standard procedures, correct answers are only considered when subjects correctly report an applied stimulus to any of the ears, disregarding the condition evaluated. This means that on every condition there are correct answers for right-ear and left-ear. Homonyms are accounted for when subjects report correctly the same paired stimuli on both ears (ex: BA "right-ear"- BA "left-ear"). Errors are intrusions (i.e., unrelated answers to applied stimuli, ex: answer "PA" when applied stimuli were "BA-DA") and missed homonyms.

2.2.4. Neuropsychological assessment and questionnaires

A test battery including the Trail Making Test A and B (Reitan and Wolfson, 1993), Stroop test (Golden, 1978), Phonemic (Benton, 1967) and Semantic fluency (Newcombe, 1969), Digits span forward and backwards (Wechsler, 2014), Logical Memory I and II Wechsler (Wechsler, 1997), Vocabulary (Wechsler, 2014), Block design (Wechsler, 2014), Purdue Pegboard (Lafayette Instrument Model 32,020) and Finger tapping (Reitan and Wolfson, 1993) was applied to obtain a cognitive profile of the participants. In addition, the Waterloo Foot Preference Questionnaire (Elias et al., 1998), and the Handedness Questionnaire (Briggs and Nebes, 1975) were used to confirm the laterality preferences of the participants, although all of the volunteers were self-declared as being right-handed. The Falls Efficacy Scale International (FES−I) was employed to evaluate fear of falling while the Norwegian version of the F-36 questionnaire (Loge et al., 1998) was used to assess health status.

2.3. Procedure

Thorough information on the study was given and informed consent was taken at the beginning of the test sessions. An initial interview was carried out, followed by the neuropsychological test battery, questionnaires and audiometry. Then, after a rest period, the participants executed the dual-task paradigm. First, they were required to only walk during 1 min in the OptoGait system to collect baseline measurements for gait. The time assigned to simple walking was based on pilot trials. After single walking, participants performed the dual-task procedure. For dual-tasking, participants were provided with a pair of wireless, noise cancelling head phones. Participants were given sufficient time to understand instructions and adjust the volume until reporting clear perception of the DL stimuli. At this stage, participants selected volume level after being presented with one example of stimulus at 80 dB. Thereafter, participants adjusted the volume over this range and up to 90 dB, which was the highest possible level of audibility for the experiment. Then, participants performed the dichotic listening at the same time that they walked in the OptoGait area. DL test started always with the Non-Forced condition (NF), followed by either the Forced-Right (FR) or Forced-Left (FL) condition, which were presented counterbalanced. Responses were recorded using a digital recorder that was placed around the participant's neck. A rest was given to the participants between DL conditions. Recording of the oral responses was registered afterwards manually. All responses were recorded and written down by one experimenter at time of testing. After the experiment was completed, both recorded and written responses were checked by a second experimenter who manually recorded all answers into the *E-prime* software to ensure reliable data. Finally, it is necessary to highlight that we intentionally did not assess DL as single task as we wanted to evaluate the impact of the experimental situation without previous knowledge.

2.4. Statistical analyses

2.4.1. Evaluation of demographics and neuropsychological tests

Group comparisons for demographics, background variables, cognitive tests and questionnaires were performed with independent *t*-tests.

2.4.2. Evaluation of DL

A series of factorial analyses of variance with repeated measures in one factor with the design 2 Group (Young-Old, Old-Old) × 2 Ear (right, left) × 3 Condition (NF, FR, FL) was used. In case of a significant omnibus test, univariate tests were performed. In case of significant interactions, multivariate tests for simple main effects were carried out.

2.4.3. Evaluation of gait

The mean and coefficient of variations (CoV) were analyzed separately on each gait parameter. Bilateral gait outcomes (i.e., values for both limbs taken together) were first analyzed and then lateralized outcomes (i.e., separate results for right and left limbs). For bilateral analyses a set of mixed-ANOVAs were conducted with the design 4 Condition (Baseline, NF, FR, FL) as the within-subjects factor × 2 Group (Young-Old, Old-Old) as the between-subjects factor. For lateralized analyses of gait, we used two-way ANOVAs with the design: 4 Condition (Baseline, NF, FR, FL) × 2 Foot (right, left) × 2 Group (Young-Old, Old-Old). In all analyses, Geisser-Greenhouse corrections were chosen when the sphericity assumption was not met. Significant interactions or main effects involving group differences were followed up with appropriate post-hoc analyses.

2.4.4. Evaluation of the effects of hearing loss

The impact of hearing loss was tested in a series of ANCOVAs for DL and gait measures by using the PTA-worst values as the covariate. As suggested by Schneider et al. (Schneider et al., 2015) all values were centered before used as covariates. Also, data were scrutinized to assure compliance of all ANCOVA assumptions, which were met.

2.4.5. Evaluation of the relationship between DL and gait

Pearson's correlations analyses were performed to assess the relationship between DL performance and lateralized results of gait. All analyses were performed with the statistical package IBM SPSS Statistics 23.

3. Results

Results for demographic variables, handedness, footedness, FES-I and SF-36 are presented in Table 1. Significant group differences in addition to age ($t\,(76) = -12.26, p < 0.001$) were found for education ($t\,(76) = 1.98, p < 0.05$) and both PTA values (best: $t\,(76) = -4.40, p < 0.001$; worst: $t\,(76) = -4.90, p < 0.001$). As expected the OO group had significantly higher PTA values than the YO participants. Also the OO group had significantly lower education. Results from the Handedness Inventory corroborated that all participants were right handed, as positives scores deviating from zero (i.e., no hand preference) indicate right-hand preference.

Table 1
Participant's demographics and characteristics by age groups.

	Young-old (n = 38)		Old-old (n = 40)	
Sex (male/female)	11/26		18/24	
	M	(*SD*)	*M*	(*SD*)
Age (years)	65.4	(2.9)	76.4	(4.8)***
Education (years)	14.0	(3.5)	12.3	(4.3)*
Height (cm)	168.8	(8.1)	170.2	(8.3)
Handedness	20.7	(3.9)	19.8	(5.2)
Footedness	12.1	(7.7)	10.8	(5.8)
FES-I	19.0	(4.1)	19.9	(3.2)
SF-36	105.2	(6.9)	105.1	(7.8)
PTA best (dB)	17.12	(7.5)	26.6	(11.1)***
PTA worst (dB)	20.38	(8.7)	31.9	(11.9)***

Note: Significant group differences are denoted by: * = $p < 0.05$; *** = $p < 0.001$.
Abbreviations: FES-I = Falls Efficacy Scale International, SF-36 = 36-item Short-Form Health Survey, PTA = pure tone average.

Table 2
Summary of auditory characteristics by group.

	Young-Old (n = 38)	Old-Old (n = 40)
	Number (%)	Number (%)
Hearing status		
Normal (< 25 dB)	26 (68.4)	10 (25)
Hearing loss (> 25 dB)	12 (31.6)	30 (75)
Interaural differences		
0–5 dB	33 (86.8)	25 (62.5)
6–10 dB	3 (7.9)	10 (25)
11–15 dB	2 (5.3)	5 (12.5)
Best ear by interaural thresholds		
0–5 dB		
Right ear	12 (31.6)	16 (40)
Left ear	14 (36.8)	6 (15)
Equal	7 (18.4)	3 (7.5)
6–10 dB		
Right ear	N/A	5 (12.5)
Left ear	3 (7.9)	5 (12.5)
Equal	N/A	N/A
11–15 dB		
Right ear	1 (2.6)	4 (10)
Left ear	1 (2.6)	1 (2.5)
Equal	N/A	N/A

Equal = same threshold on both ears. N/A = not available.

3.1. Audiometric characteristics

As observed in Table 2, the large majority of subjects in the YO group (68.4%) had normal hearing while only 25% of the OO group had it. As for interaural differences, most of the YO participants, namely 86.8% of this sample, had small threshold differences between ears of not > 5 dB. Less than 8% differed by 6–10 dB and only 5% had a difference between 11 and 15 dB. In the OO group 62.5% had a difference equal or lower than 5 dB; 25% presented interaural difference between 6 and 10 dB and 12% had a difference over 11 dB.

Regarding characteristics of the most sensitive ear on each group, we observed that in the YO group 34.2% of the participants (n = 13) had better sensitivity with right ear, 47.4% with left (n = 18) and 18.4% (n = 7) had equal sensitivity thresholds on both ears. For the OO group, the large majority of participants (62.5%, n = 25) had better sensitivity on right ear while only 30% (n = 12) had better thresholds with left ear and 7.5% (n = 3) presented equal sensitivity in both ears.

Table 3
Mean (*M*) and Standard deviations (*SD*) by age group for MMSE and neuropsychological tests.

	Young-Old (n = 38)		Old-Old (n = 40)		*t*-score (76)
	M	*SD*	*M*	*SD*	
MMSE	29.08	1.32	28.33	2.20	0.87
TMT (seconds)					
A	34.85	16.81	42.20	14.16	−2.09[a]
B	75.36	21.38	107.9	33.70	−5.01[b]
Stroop Test					
Word	91.92	14.39	78.53	15.49	3.95[c]
Color	64.97	11.28	55.25	8.69	4.27[c]
Color/word	34.45	7.89	27.10	7.04	4.34[c]
Digit span					
Forwards	9.11	1.72	8.08	1.77	2.60[b]
Backwards	8.11	1.85	7.50	1.75	1.48
Log Memory I	10.39	3.10	10.58	3.80	−0.22
Log Memory II	14.42	3.74	13.53	4.28	0.98
Vocabulary	33.05	5.72	30.70	8.43	1.44
Pegboard					
Right hand	13.08	2.17	10.58	2.14	5.11[c]
Left hand	11.95	2.08	10.23	2.08	3.62[c]
Both hands	10.16	1.72	8.33	1.60	4.83[c]
Assembly	5.92	1.14	4.70	1.18	4.60[c]
Block design	36.00	10.89	32.72	9.91	1.38
Finger tapping					
Right	40.38	10.82	39.80	11.32	0.23
Left	38.60	9.71	36.04	9.95	1.14
Grip strength					
Right hand (kg)	31.75	8.31	38.78	11.83	−3.04[b]
Left hand (kg)	30.54	7.53	37.39	11.47	−3.13[b]
Phonemic fluency					
Correct answers	13.67	3.85	12.02	3.52	1.96
Repetitions	0.37	0.40	0.63	0.60	−2.19[a]
Semantic Fluency					
Correct answers	17.49	3.99	15.06	2.52	3.17[b]
Repetitions	0.35	0.37	0.46	0.71	−0.78

Note: MMSE = Mini Mental State Examination; TMT = Trail making test.
[a] $p < 0.05$.
[b] $p < 0.01$.
[c] $p < 0.001$.

3.2. Neuropsychological results

These data are shown in Table 3. There were found significant group differences in executive functions (TMT A, $p < 0.05$; TMT B, $p < 0.001$; Stroop test, $p < 0.001$) and attention (Digits span forwards, $p < 0.01$). Further significant differences were found for psychomotor function (all Pegboard measurements, $p < 0.001$), grip strength (right and left, $p < 0.01$), phonemic repetitions ($p < 0.05$) and semantic fluency answers ($p < 0.01$).

3.3. Dichotic listening

After controlling for hearing status there were no significant group differences in number of correct answers ($F(1, 75) = 1.12$, $p = 0.29$). The same applied for laterality indexes and homonyms. These results are presented in Table 4. However, the errors significantly differed between groups after controlling for PTA values [it is necessary to remind that according to the standard DL methodology, errors are defined as any answer not matching the applied stimuli. For instance if the syllables "BA-DA" were presented respectively to right and left-ear and the participants said "TA", that will be considered a real error]. A closer analysis to these data showed that errors contained real errors but also several omissions. It turned out that many participants did not emit any answer in several trials. For this reason, we decided to calculate the total amount of errors and then, divided it into real errors and omissions. As depicted in Fig. 1, omissions increased proportionally from NF to FL condition. In the NF condition almost all type of incorrect answers were real errors. Percentage of errors varies from 22.2% for the YO to 33.3% in the OO group. In FR condition, real errors decreased in both groups at expense of an increment in omissions. The percentage of total errors committed in the FR condition rises to 30.5% for YO and to 37.5% for OO. In the FL condition, again we observed an increment in omissions and in the total number of errors, especially for the YO group. This time, the percentage of total errors reaches 36.1% for YO and 38.8% for OO.

Stacked bars show real errors in solid color and omitted responses in lined pattern.

3.4. Bilateral gait outcomes (see Table 5)

3.4.1. Mean values

Step length showed a significant main effect for Condition and Group and a significant interaction between Condition X Group. Tests for simple main effects showed that group differences were present across all conditions with constant higher values for the YO group. However, when we controlled for hearing status the interaction was no longer significant, though the effect of Condition and Group remained. On *Gait speed*, there was a main effect of Condition and Group and a significant interaction. After controlling for hearing, results were not altered. Again the YO group displayed higher values than the OO group. For *Step width* no main effect of Condition or interaction with Group were found. Though, a main effect of Group was observed which was removed after controlling for PTA values in which the OO group presented wider step widths than the YO group. Finally, results for *Stride length* showed a main effect of Condition and Group but no interaction. Controlling for PTA values did not remove the significant effects in which the YO group presented higher values.

3.4.2. CoV values

There were limited significant effects on variability of gait. For step length, a significant main effect of Condition and Group were found but no interactions. The effect of Group turned non-significant after controlling for hearing status. The other significant result found on CoVs existed for gait speed in which the mixed ANOVA revealed only a main effect of Condition. This finding remained significant after controlling for hearing status.

3.5. Lateralized gait outcomes (see Table 6)

3.5.1. Mean values

Step length showed a main effect of Condition (F (3, 120.06) = 36.52, $p < 0.001$), Group (F (1, 76) = 16.31, $p < 0.001$; higher values for the YO group) and a significant interaction for Condition X Group (F (3, 120.06) = 3.67, $p < 0.05$). However, controlling for hearing status on these analyses affected the results for Group (F (1, 75) = 3.58, $p = 0.06$) as well as the interaction Condition X Group (F (3, 83.35) = 0.89, $p = 0.36$) which no longer were significant.

Gait speed showed a main effect of Condition (F (3, 166.69) = 62.82, $p < 0.001$) and Group (F (1, 76) = 17.9, $p < 0.001$; higher values for the YO group). No significant main effect of Foot (F (1, 76) = 16.31, $p < 0.001$) or any significant interaction existed. Controlling for hearing status did not change these results. Nonetheless, there was a significant three-way interaction "Condition X Foot X Group" (F (3, 85.63) = 4.01, $p < 0.05$) after controlling for hearing status. Follow-up pairwise comparisons demonstrated that significant group differences existed for right $p < 0.05$ and left foot $p < 0.01$ across conditions. The YO group displayed a mean of 1.095 (m/s) for right foot, while the OO group presented a mean of 0.992 (m/s). As for the left foot, the mean speed displayed for YO was 1.101 (m/s) and 0.983 (m/s) for the OO group. Further scrutiny of the three-way interaction showed that the Non-Forced condition was a challenging situation for the OO

Table 4
Dichotic listening means (*M*) and standard deviations (*SD*).

	NON-FORCED CONDITION						FORCED-RIGHT CONDITION						FORCED-LEFT CONDITION					
	Right Ear		Left Ear				Right Ear		Left Ear				Right Ear		Left Ear			
	M	*(SD)*	*M*	*(SD)*			*M*	*(SD)*	*M*	*(SD)*			*M*	*(SD)*	*M*	*(SD)*		
	Correct answers						Correct answers						Correct answers					
Young-Old	13.0	(3.2)	9.0	(3.1)			13.2	(4.8)	7.5	(2.8)			10.7	(4.6)	8.7	(3.7)		
Old-Old	10.4	(3.8)	7.9	(3.4)			11.2	(4.9)	7.0	(3.6)			9.2	(5.0)	9.0	(4.2)		
	Laterality index						Laterality Index						Laterality Index					
	M		*(SD)*				*M*		*(SD)*				*M*		*(SD)*			
Young-Old	18.2		(22.2)				25.0		(26.9)				9.5		(27.6)			
Old-Old	14.0		(30.1)				23.4		(34.7)				3.4		(36.8)			
	Homonyms						Homonyms						Homonyms					
	M		*(SD)*				*M*		*(SD)*				*M*		*(SD)*			
Young-Old	4.7		(1.1)				3.9		(1.9)				3.8		(1.8)			
Old-Old	4.2		(1.2)				3.6		(1.4)				3.7		(2.2)			
	Errors Non-Forced						Errors Forced-Right						Errors Forced-Left					
	Total		*Real*		*Omissions*		*Total*		*Real*		*Omissions*		*Total*		*Real*		*Omissions*	
	M	*(SD)*	*M*	*(SD)*	*M*	*(SD)*	*M*	*(SD)*	*M*	*(SD)*	*M*	*(SD)*	*M*	*(SD)*	*M*	*(SD)*	*M*	*(SD)*
Young-Old	8.2	(3.5)	8.0	(3.6)***	0.2	(0.6)	11.0	(6.3)	7.0	(3.9)*	4.0	(6.1)	11.2	(7.1)	6.3	(3.9)*	4.8	(6.8)
Old-Old	11.8	(4.9)	11.1	(3.7)	0.9	(2.2)	13.7	(7.5)	9.2	(4.6)	4.5	(5.8)	13.3	(6.6)	9.0	(4.9)	4.1	(5.1)

Note: All significant group differences presented are true after controlling for hearing status are denoted by: * = $p < 0.05$; *** = $p < 0.001$.

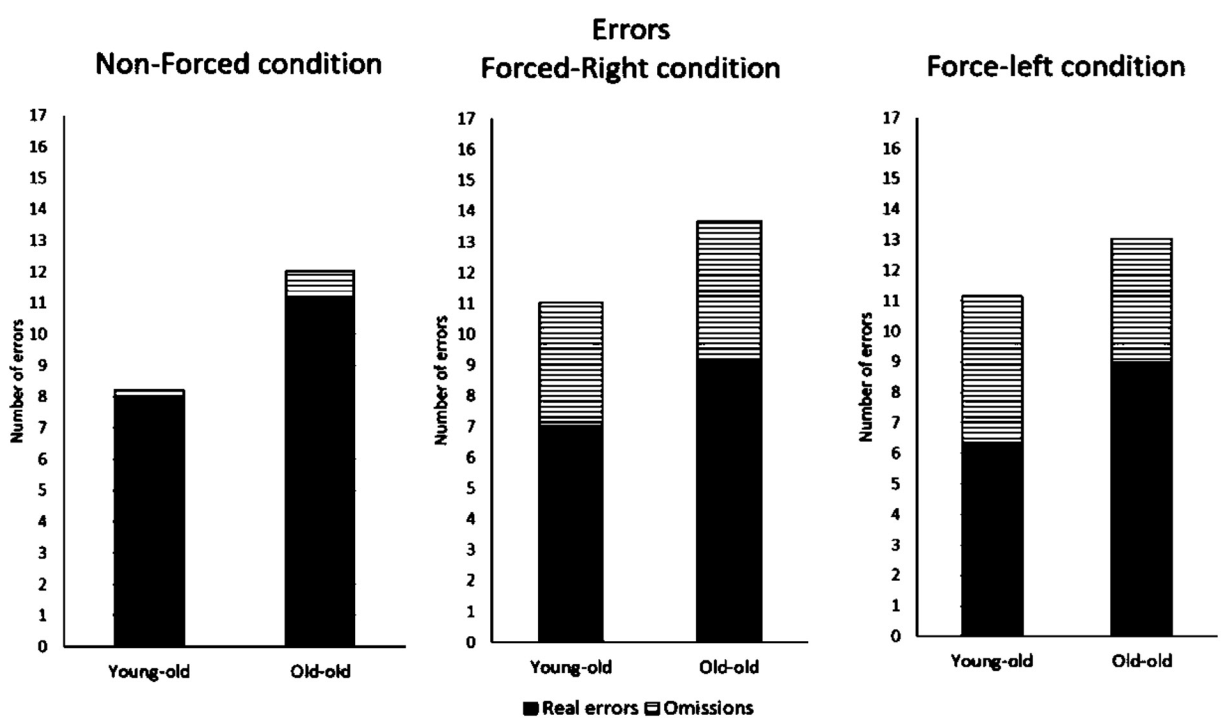

Fig. 1. Dichotic listening results for errors by condition and age group.

group who displayed slower speed on the left foot (0.99 m/s) as compared to their right foot (1.03 m/s).

Step width showed only a significant main effect of Foot (F (1, 76) = 14.1, $p < 0.001$) and Group (F (1, 76) = 7.8, $p < 0.01$; higher values for the OO group). When controlling for hearing the main effect of Foot remained unchanged but not that of Group (F (1, 75) = 1.34, p = 0.25). These data showed that right foot presents wider values in both groups (YO = 9.1 cm; OO = 9.8 cm) as compared to the left side (YO = 8.4 cm; OO = 9.2 cm). It is important to remind that step width for each limb is calculated from the lateral displacement of the specific foot based on its previous position.

Stride length, only significant main effects for Condition (F (3, 167.79) = 59.01, $p < 0.001$) and Group (F (1, 76) = 19.7, $p < 0.001$; higher values for the YO group) existed. Controlling for PTA values did not affect these results.

3.5.2. CoV values

Results of CoV data show limited significant results. In step length, a main effect of Condition (F (3, 143.44) = 4.65, $p < 0.05$) and Group (F (1, 76) = 11.24, $p < 0.001$) were found, but effects disappeared after controlling for hearing status. The same applies for gait speed. As for variability in step width, we did not find significant effects (see Table 5). The only significant result on CoV relates to stride length, as this variable was the only one showing a main effect of Foot (F (1,

Table 5
Results for bilateral gait parameters.

	Condition								RMANOVA, *p* Condition/Interac./Group	ANCOVA, *p* Interac./Group/PTA
	Baseline		Non-Forced		Forced-Right		Forced-Left			
	Y-O	O-O	Y-O	O-O	Y-O	O-O	Y-O	O-O		
	M (*SD*)	*M* (*SD*)	*M* (*SD*)	*M* (*SD*)	*M* (*SD*)	*M* (*SD*)	*M* (*SD*)	*M* (*SD*)		
Mean										
Step length	67.5 (6.0)	61.7 (8.1)	65.0 (6.1)	58.1 (9.1)	63.6 (6.2)	56.0 (9.3)	63.7 (6.0)	56.0 (9.3)	0.001/0.047/0.001	NS/0.023/0.001
Gait speed	1.2 (0.1)	1.1 (0.2)	1.0 (0.2)	1.0 (0.2)	1.1 (0.2)	0.9 (0.2)	1.1 (0.2)	0.9 (0.2)	0.001/0.001/0.001	†/**0.034**/**0.003**
Step width	8.1 (2.7)	9.5 (2.2)	8.4 (2.4)	9.8 (2.4)	8.3 (2.5)	10.3 (4.6)	8.5 (2.4)	10.3 (3.9)	NS/NS/**0.004**	NS/NS/**0.003**
Stride length	138.0(14.0)	124.9(16.0)	132.3(13.1)	118.5(17.9)	130.0(13.5)	113.0(19.0)	130.0(12.1)	113.6(18)	0.001/NS/0.001	NS/0.011/0.001
CoV (%)										
Step length	5.1 (2.8)	6.1 (4.1)	5.4 (2.8)	7.1 (3.8)	5.4 (3.8)	9.1 (5.6)	5.4 (3.3)	8.4 (5.1)	0.01/NS/0.001	NS/NS/**0.002**
Gait speed	4.6 (3.4)	6.2 (5.6)	6.4 (4.8)	6.9 (4.4)	6.5 (7.7)	11.0(14.7)	6.4 (7.4)	9.5 (13.1)	0.034/NS/NS	NS/NS/NS
Step width	76.5(39.0)	75.8(29.2)	81.8(31.8)	71.8(23.8)	87.1(33.6)	79.9(29.9)	82.4(32.7)	79.3(32.9)	NS/NS/NS	NS/NS/NS
Stride length	8.9 (6.4)	7.4 (8.8)	10.0 (9.0)	10.7(12.1)	10.0(10.3)	9.4 (8.6)	10.6 (8.9)	9.1 (8.7)	NS/NS/NS	NS/NS/NS

Note: Interaction marked with † refer to = Condition X Group $p = 0.049$. Units for Step length, Step width and Stride length = cm.; units for Gait speed = m/s.
Abbreviations: Y-O = young-old group; O-O = old-old group; *M* = mean; *SD* = standard deviation; RMANOVA = repeated measures analysis of variance; ANCOVA = Analysis of covariance; CoV = Coefficient of Variation; Interac. = Interactions; PTA = worst Pure Tone Audiometry values; NS = Non Significant.
CoV = Calculated with the formula: [mean/*SD*] × 100%.

76) = 5.65, $p < 0.05$), even after controlling for hearing status (F (1, 75) = 5.76, $p < 0.05$). These data suggest higher variability on stride length of the right limb in both groups, especially during the FR condition. Changes in CoV are not straightforward since increment of variability did not followed level of attentional difficulty of the conditions.

3.6. Associations between DL performance and gait parameters

Pearson's correlations coefficients are shown in Table 7. In these analyses, we examined the associations between correct numbers of answers (i.e., answers matching the applied stimuli) for right or left ear and gait outcomes from right and left foot separately. Results demonstrated that right ear answers across conditions were significantly associated with gait results in the 3 DL conditions, while correlations with left-ear answers were only found in the NF condition.

3.6.1. Correlations with mean values of gait and right-ear answers

Table 7 shows that right ear answers had the higher number of correlations with gait parameters across conditions. Mostly, right ear answers were significantly related with gait measures bilaterally, indicating that as number of responses from right ear increases the higher are mean values for gait. Though, few mean values showed lateralized associations.

Table 6
Mean and Standard deviations for gait parameters by foot expressed in mean values and coefficients of variation (CoV).

Gait variables	Conditions								Two-way ANOVA, *p* Condition/foot/inter/group	Two-way ANCOVA, *p* Foot/inter/group/PTA
	Baseline		Non-forced		Forced-right		Forced-left			
	Y-O	O-O	Y-O	O-O	Y-O	O-O	Y-O	O-O		
	M (*SD*)	*M* (*SD*)	*M* (*SD*)	*M* (*SD*)	*M* (*SD*)	*M* (*SD*)	*M* (*SD*)	*M* (*SD*)		
Mean										
Step length R	65.9 (12.2)	61.6 (8.2)	65.0 (6.5)	58.1 (9.6)	63.4 (6.6)	55.6 (9.6)	63.6 (6.0)	55.7 (9.7)		
Step length L	67.4 (6.1)	61.8 (8.0)	65.0 (5.8)	58.3 (8.7)	63.8 (5.8)	56.3 (9.1)	63.8 (6.0)	56.1 (9.1)	0.001/NS/0.038/0.001	NS/NS/NS/0.002
Gait speed R	1.2 (0.1)	1.1 (0.2)	**1.1 (0.1)**	**1.0 (0.3)**	1.1 (0.2)	0.9 (0.2)	1.1 (0.2)	0.9 (0.2)		
Gait speed L	1.2 (0.1)	1.1 (0.2)	**1.1 (0.2)**	**0.9 (0.2)**	1.1 (0.2)	0.9 (0.2)	1.1 (0.2)	1.0 (0.2)	0.001/NS/NS/0.001	NS/†/**0.01**/**0.001**
Step width R	8.3 (3.5)	9.9 (2.2)	8.6 (2.5)	9.6 (4.2)	8.6 (2.8)	10.5 (4.4)	8.9 (2.7)	10.8 (3.7)		
Step width L	7.6 (2.6)	9.0 (2.8)	8.1 (2.5)	9.5 (3.1)	8.1 (2.2)	10.1 (4.9)	8.1 (2.1)	9.9 (4.1)	NS/**0.001**/NS/**0.007**	**0.001**/NS/NS/**0.001**
Stride length R	137.5(12.7)	125.1(16.1)	132.1(12.4)	118.8(18.0)	130.7(14.4)	113.2(19.0)	130.3(12.7)	113.8(18.2)		
Stride length L	138.3(15.3)	124.7(16.4)	132.4(14.0)	118.1(18.1)	129.3(12.9)	112.9(19.1)	129.6(12.0)	113.5(17.8)	**0.001**/NS/NS/**0.001**	NS/NS/**0.01**/**0.001**
CoV (%)										
Step length R	4.8 (3.0)	6.1 (3.8)	4.7 (2.4)	6.8 (3.7)	5.2 (3.5)	8.6 (6.1)	5.2 (2.5)	8.0 (5.4)		
Step length L	4.7 (3.2)	5.7 (5.0)	5.4 (3.5)	6.8 (4.1)	5.2 (4.0)	8.7 (5.7)	5.3 (4.1)	8.2 (5.1)	**0.013**/NS/NS/**0.002**	NS/NS/NS/**0.001**
Gait speed R	4.7 (4.3)	6.5 (6.1)	6.6 (5.1)	6.7 (4.7)	6.3 (8.0)	10.4 (15.3)	6.4 (7.1)	9.8 (14.2)		
Gait speed L	4.3 (2.5)	6.0 (5.6)	6.4 (4.8)	7.1 (4.4)	6.5 (7.7)	11.4 (14.6)	6.4 (7.7)	9.5 (13.1)	**0.04**/NS/NS/NS	NS/NS/NS/NS
Step width R	78.1(33.0)	69.1(24.5)	73.8(23.0)	65.6(19.2)	83.6(31.4)	73.7(23.4)	77.3(29.3)	72.3(28.1)		
Step width L	71.1(34.9)	77.1(34.2)	77.5(32.0)	71.2(25.1)	85.3(35.6)	76.0(26.8)	78.3(28.6)	76.9(29.0)	NS/NS/NS/NS	NS/NS/NS/NS
Stride length R	7.6 (7.8)	7.1 (7.8)	9.2 (8.9)	11.2(13.7)	10.8 (11.7)	10.0(10.9)	10.8 (9.9)	8.8 (9.1)		
Stride length L	7.5 (6.7)	6.3 (9.0)	9.4 (10.9)	9.1 (9.6)	7.9 (9.4)	7.8 (6.1)	8.9 (8.9)	8.4 (8.4)	NS/**0.02**/NS/NS	**0.02**/NS/NS/NS

Note: Interaction marked with † refer to = Condition X Foot X Group $p < 0.05$. Data in bold denotes the significant interaction. Units for Step length, Step width and Stride length = cm.; units for Gait speed = m/s.
Abbreviations: Y-O = Young-Old group; O-O = Old-Old group; *M* = mean; *SD* = standard deviation; RMANOVA = repeated measures analysis of variance; ANCOVA = Analysis of covariance; CoV = Coefficient of Variation; Interac. = Interactions; PTA = worst Pure Tone Audiometry values; NS = Non Significant.
CoV = Calculated with the formula: [mean/*SD*] × 100%.

Table 7
Pearson correlations between correct matched answers by ear and lateralized gait outcomes per DL condition.

Gait parameters	Right ear answers			Left ear answers
	Non-forced	Forced-right	Forced-left	Non-forced
Right foot				
Step length				
Mean	NS	NS	0.29[a]	NS
CoV	NS	NS	−0.37[b]	NS
Stride length				
Mean	NS	0.23[a]	0.27[a]	NS
CoV	NS	NS	NS	0.45[b]
Gait speed				
Mean	NS	0.26[a]	0.35[b]	NS
CoV	NS	NS	−0.23[a]	NS
Left foot				
Step length				
Mean	0.27[a]	0.24[a]	0.31[b]	NS
CoV	NS	NS	−0.37[b]	NS
Stride length				
Mean	NS	NS	0.27[a]	NS
CoV	NS	NS	NS	0.37[b]
Gait speed				
Mean	0.25[a]	0.23[a]	0.35[b]	NS
CoV	NS	NS	−0.25[a]	NS

Note: Only significant correlations are presented. NS = non significant results.
[a] $p < 0.05$.
[b] $p < 0.01$.

3.6.2. Correlations with CoV values of gait

Significant associations between matching answers and CoVs in gait parameters were found in the NF and FL condition. Right ear answers were negatively associated with bilateral CoVs of step length and speed in FL condition. In contrast, left ear answers were positively associated to bilateral CoVs of stride length in the NF condition. These latter correlations were the highest encountered showing $r = 0.45$ ($p < 0.01$) for right foot and $r = 0.37$ ($p < 0.01$) for left foot. All-in-all, data suggest that higher number of right ear answers when focus of attention is intended to the left ear decrease CoVs in speed and step length, while higher left ear responses in NF condition are linked to higher variability in stride length.

4. Discussion

The first main finding of the present investigation indicates that lateralized focus of attention alters asymmetrically in three of the gait parameters evaluated in healthy older adults. These asymmetries were observed on step width, gait speed and variability of stride length.

Results for step width demonstrated that right foot displayed higher values than left foot in both groups and in all conditions including baseline. This finding suggests that asymmetries in step width are not only related to the dual-task paradigm but are an intrinsic characteristic of older adults. The asymmetries encountered in the baseline condition should be regarded as a result of the overground methodology employed in our study. Usually, subjects are required to walk within a specific short distance and not during a time period. These results agree with earlier data showing that step width differentiates between young and older adults (Hamacher et al., 2011). Even though, no significant interactions were found, we observed that step width asymmetries increased during DL execution, particularly for OO subjects during the forced-left condition. In this condition, the OO group presented a between-feet difference of almost 1 cm (10.8 cm for left foot vs 9.9 cm for right foot) while their amount of correct responses from right and left ear was almost equal. These data show the difficulty from the OO participants to focus and/or process left side stimuli, which results in enlarged step width being particularly higher for the right foot.

The next finding showing the effects of lateralized control of attention was observed on gait speed in the NF condition. This time, the OO group emitted a higher number of right-ear answers while they demonstrated slower speed with left foot. Though, these participants also had the highest number of real errors in all DL conditions. All together, these data suggest that the NF condition is a challenging one for the OO group due to increased uncertainty on attentional focus and perceptual constraints. Thus, it appears that the symmetry of walking speed is sensitive to hesitation in deciding which source of information has to be attended. The last asymmetric finding was that of increased stride length variability in both groups, specifically on their right foot. It is plausible that higher variability in this measure occurred due to reductions in rhythmicity caused by other gait asymmetries (LaRoche et al., 2012).

Taken together the above findings, it is evident that asymmetric effects occurred mostly on the right limb. Our interpretation is that our paradigm exerts a more accentuated effect on right foot due to higher involvement of the left hemisphere. In spite of the lateralized focus of attention required on DL to both left and right ear, DL remains a language task that relies on the ultimate activation of left hemisphere to process the auditory signal. Increased loading on left hemisphere may destabilize mechanisms associated with contralateral control of lower limbs' movements.

4.1. Possible mechanisms underlying the effect of DL on gait

The asymmetries encountered showed that DL perturbs asymmetrically "pace" measures of gait. Verghese et al. (2007) proposed that velocity and length measures represent the "pace" aspect of gait, which is associated with executive functioning. Our data corroborated this assertion as DL relies not only on focusing attention to one side, but on mechanisms necessary for inhibiting the competing stimulus. The fact that DL disturbs these parameters asymmetrically can be understand as overloading of common brain areas necessary for accomplishing both tasks, which we suggest are related to frontal lobe circuitry. Although, the mechanisms of how the brain operates under dual-tasking remains an open question, it is plausible that proper wiring of frontal areas through integrity of corpus callosum (CC) is behind the observed asymmetries. The age-related thinning of CC has been proved central for DL performance (Westerhausen et al., 2015) and it also has been reported as important for gait and balance (Bhadelia et al., 2009)). In addition, the CC might also play a main role in the context of dual-tasking where complex sensorimotor integration is required for maintenance of balance and integration of visual and proprioceptive cues. Information about the integrity of CC in our participants should have clarified this matter and future research may address this issue.

4.2. Hearing status as moderator of attention and gait disturbances in dual-tasking

The second goal of the present study was to evaluate the effects of hearing loss on DL execution and gait. As expected, hearing loss hampered DL performance, as controlling for hearing status ruled out significant group differences in this test. However, the neuropsychological results demonstrated that both groups differed in cognitive capacities, notably in those assessing similar functions to the DL, such as the Stroop test and the TMT that evaluate executive functions and inhibition.

Hearing loss also modulated the effects on gait during dual-tasking. The moderating effects of hearing loss were first evaluated in bilateral gait measures, that is, when values for both limbs were taken together. Prior to controlling for hearing loss, we found significant group differences in the mean of all gait parameters including one variability measure on step length, which agrees with previous investigations (Hollman et al., 2011). However, after controlling for hearing status, many of the significant effects and interactions were partialled out. Also, after controlling for hearing loss one of the asymmetric effects (i.e., gait speed) was encountered, which implies that hearing loss masked this asymmetry. These findings suggest that hearing status in older adults, moderates result of the dual-task paradigm. These data need to be assembled to previous research showing that moderate to greater hearing impairments, i.e. PTA > 40 dB, are associated with falls and risk of developing frailty (Kamil et al., 2016). Our data suggest that even milder levels of hearing loss (25 dB–40 dB) in healthy older adults, altered spatiotemporal measures of gait. As previous data have highlighted, age-related hearing loss is associated with falls and slower gait speed. In our study, group effects on gait speed remained after controlling for hearing status. However, the means of step width and step length seemed to be sensitive to the effects of hearing status as significant group differences disappeared after controlling for PTA values.

Notwithstanding, in spite of finding that hearing status modulates gait and cognitive results, caution is required in the interpretation of these data as it is not possible to isolate the age-related variance from the hearing-related variance. The issue of whether controlling for degree of hearing loss helps or hinders our understanding of an age-related phenomenon has been addressed in the literature previously (Martin et al., 1991). Some authors warns against indiscriminate use of statistical techniques to control for hearing loss "*without careful consideration of theoretical foundations*" (Martin et al., 1991). In the present study, we have presented thoroughly a paradigm for lateralized auditory attention that relies, among many mechanisms, on the correct perceptual recognition of an auditory signal. We believe that even though we cannot assert that hearing loss is the only factor modulating the reported effects on gait and cognition, it would also be biased to deny its role to accomplish the present experimental situation. In line with earlier research pointing to associations between walking difficulty and hearing acuity in age-adjusted models (Viljanen et al., 2009) our findings suggest that hearing loss cannot be underestimated as an important factor modulating group differences on gait asymmetries.

4.3. Association between DL conditions and gait

Overall, right ear answers had the most significant correlations with gait measurements, especially during the Forced-Left situation. All coefficients of correlation were rather modest, even if all of them were significant. Still, these data are suggestive as number of correlations were scarce in NF condition and they increase gradually in the FR and became spread in the FL condition. All correlations of right-ear answers with mean values of gait were positive while correlations with CoVs were negative, indicating that correct right-ear responses are related to larger mean values and lower gait variability in all participants. According to the standard procedure, any answer matching an applied stimuli to right or left ear is a correct answer. Attending to right-ear when the contrary is required can be regarded as maladaptive and an indication of difficulties with top-down attentional control, our interpretation is that increased number of right-ear answers secure participants to preserve a safe walk. Even though older adults experience some degree of hearing loss, they have developed through a long life a good capacity to process information from right ear. This peculiarity allows a compensatory strategy to avoid insecure walking as processing right-side information is not related to increased gait variability, which leads to deteriorated stepping control and falls in older adults (Dingwell et al., 2017). Thus, limitations in attending left-ear information help older adults to cope with sensory loss and cognitive demands during the challenging situation of walking, listening and talking. We suggest that an automatic adaptation exists in right-handed older persons to avoid listening to the left side during dual-tasking and avoid the risk of falling.

Finally, the correlations observed for left ear answers were probably the most clear-cut associations as they were only present on CoVs of both feet in stride length during the NF condition. These correlations were positive and somewhat stronger than the previous set of results, suggesting that when participants report left-ear stimuli in the NF condition stride length variability increases significantly. Accordingly, these data indicate that by attending left-ear information the risk of a fall increases since stride length variability has been found to be a good predictor of injurious falls (Verghese et al., 2009).

4.4. Limitations of the study

Although, we wanted to understand the effects of our paradigm in naive subjects, the lack of single task results for DL in our investigation is a limitation. No correlations with the errors are presented, which is another limitation of the study. The reason for not including these correlations was the reduced and variable number of errors per subject and condition, which is disproportional to the available gait data. Another potential limitation is the difference in time concerning the baseline trial for walking (1 min.) vs the dual-task conditions (3 min.). It can be argued that comparisons between conditions and the baseline are not equivalent, as they do not match exact number of walking cycles. However, according to guidelines for appropriate evaluation of spatiotemporal analysis of gait in older populations there should be a minimum of 3 consecutive gait cycles by limb to obtain correct evaluations (Kressig and Beauchet, 2006). Thus, our participants performed between 30 and 50 gait cycles during the 1 min baseline trial, which allows calculation of appropriate estimates of spatiotemporal gait parameters. Future investigations should assess whether results are affected by equal number of gait cycles.

5. Conclusions

The present study demonstrates that in right-handed older adults lateralized auditory attention affects gait asymmetrically. It also became evident that hearing status ranging from normal to mild hearing loss modulates the effects of focus of auditory attention on gait. Finally, we showed that focus of attention to the right side do not compromise gait. It can even be argued that attending to the right side is beneficial, as participants displayed larger and wider steps, larger strides and less gait variability while listening to right-ear stimuli. On the contrary, attending to left-side stimuli increases stride length variability. In summary, the present investigation demonstrates that DL is a convenient test to evaluate the interplay of gait, hearing and attentional control during overground walking and should be employed in future work as part of multifactorial analysis. For instance, future studies may address the neural correlates of the reported asymmetries as well as gender effects on lateralized gait disturbances. The issue of asymmetries on left-handed participants is warranted as we only examined right-handed persons. Correspondingly, application of the dual-task paradigm in geriatric patient populations affected by cognitive dysfunctions would be highly valuable as information from patients will put in perspective the findings reported in the present investigation.

Acknowledgments

We thank Matilde Klaussen for helping with data acquisition.

Disclosure statement

There are no conflicts of interest.

Funding

Financial support was received from the Faculty of Health Sciences, University of Tromsø (2016/5455), Norway and from the Norwegian Health Association (2014/888) (Nasjonalforeningen for folkehelsen).

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Paper II

Gorecka, M. M., Vasylenko, O., & Rodríguez-Aranda, C. (2020). Dichotic listening while walking: A dual-task paradigm examining gait asymmetries in healthy older and younger adults. *Journal of Clinical and Experimental Neuropsychology, 42*(8), 794-810. Doi: 10.1080/13803395.2020.1811207

Journal of Clinical and Experimental Neuropsychology

ISSN: (Print) (Online) Journal homepage: https://www.tandfonline.com/loi/ncen20

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JOURNAL OF CLINICAL AND EXPERIMENTAL NEUROPSYCHOLOGY
2020, VOL. 42, NO. 8, 794–810
https://doi.org/10.1080/13803395.2020.1811207

Dichotic listening while walking: A dual-task paradigm examining gait asymmetries in healthy older and younger adults

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ABSTRACT

Dual-task studies have employed various cognitive tasks to evaluate the relationship between gait and cognition. Most of these tests are not specific to a single cognitive ability or sensory modality and have limited ecological validity. In this study, we employed a dual-task paradigm using Dichotic Listening (DL) as concomitant cognitive task to walking. We argue that DL is a robust task to unravel the gait-cognition link in different healthy populations of different age groups. Thirty-six healthy older adults (*Mean* = 67.11) and forty younger adults (*Mean* = 22.75) participated in the study. DL consists of three conditions where spontaneous attention and attention directed to right or left-ear are tested while walking. We calculated dual-task costs (DTCs) and percent of baseline values for three spatio-temporal gait parameters as compared to single-walking during three DL conditions. Results showed that both groups had larger DTCs on gait during volitional control of attention, i.e., directing attention to one specific ear. Group differences were present across all DL conditions where older adults reported consistently less correct stimuli than younger participants. Similar findings were observed in the neuropsychological battery where older participants showed restricted abilities for executive functioning and processing speed. However, the main finding of this investigation was that younger adults exhibited unique adjustments in step length variability as shown by changes in DTCs and percent of baseline values. Particularly, an asymmetric effect was observed on the young group when attending right-ear stimuli. We interpreted this gait asymmetry as a compensatory outcome in the younger participants due to their optimal perceptual and motor abilities, which allow them to cope suitably with the dual-task situation. Many studies suggest that gait asymmetries are indicators of pathology, the present data demonstrate that gait asymmetries arise under specific constraints in healthy people as an adaptation to task requirements.

ARTICLE HISTORY
Received 27 April 2020
Accepted 7 August 2020

KEYWORDS
Dual-task; dichotic listening; healthy aging; walking over-ground; asymmetry

Introduction

Aging is associated with changes in cognition and motor functions. Specifically, these changes affect gait in older adults (Montero-Odasso et al., 2012; Morris et al., 2016). In order to address the interrelation between walking and cognition, a classical method known as dual-task paradigm has been employed. Dual-task experiments require subjects to perform two tasks simultaneously in order to measure the influence of a primary task on a secondary task. Thus, the dual-task paradigm is utilized in gait studies by simply asking individuals to walk while they perform in parallel a cognitive task (Pashler, 1994). A challenge in this line of research is the fact that numerous cognitive tasks have been used as concurrent tasks in dual-tasking and these are either not specific to one cognitive function or too intricate that findings cannot be generalized to everyday situations (for review Beauchet et al., 2005; Boisgontier et al., 2013; Patel et al., 2014).

Al-Yahya et al. (2011) showed that the cognitive tasks most recurrently employed to challenge gait were those requiring mental tracking. However, mental tracking tasks exist in various sensorial modalities and in a diversity of type of tasks that it becomes challenging to unravel how specific cognitive demands affect specific gait parameters (Shumway-Cook et al., 1997). For this reason, our group has applied a Dichotic Listening (DL) task, which is a robust test for the assessment of central auditory language processing, laterality, and interhemispheric interactions as well as divided and sustained attention.

DL and aging effects

In general, DL tasks consist in applying different stimuli (e.g., words, numbers, or syllables) to each ear at the same time (Bryden, 1988). One dichotic listening approach widely employed is the Bergen Dichotic Listening Task (Hugdahl & Andersson, 1986), which we have selected. In

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Supplemental data for this article can be accessed here.

this task, different consonant-vowel syllables are presented simultaneously to each ear in three conditions. In the first condition (Non-Forced, NF) participants report freely the stimuli that seem most salient. Then, in the other two conditions subjects are asked to either report stimuli from right or left-ear while inhibiting stimuli from the opposite ear (Forced Right/Left, FR/FL). Due to the decussation of the auditory pathways, right-handed persons report more likely responses from the right ear and such a phenomenon is known as the "Right Ear Advantage" (REA), which reflects a dominant left-hemisphere processing for language (Asbjørnsen & Hugdahl, 1995; Bryden, 1988; Kimura, 1967). This peculiarity in right-handed individuals causes that attending to the left side becomes more demanding. Thus, the increment in cognitive demands in DL, from NF to the FR and FL condition, makes possible to manipulate attentional demands on three levels in the same sensory modality (Hugdahl et al., 2009). For this reason, DL is a valuable tool to assess attentional functions across the life span. In fact, there exists an undisputable age-related effect in DL performance, where younger adults outperform older adults even when controlled for hearing loss (Hommet et al., 2010). In fact, younger adults are more capable to attend to one side and inhibit stimuli from the other. However, older adults do not differ from younger subjects when instructed to report from the right side. The main age-related difference is that older adults display reduced ability to report stimuli presented to the left-ear. (Andersson et al., 2008; Hällgren et al., 2001; Jerger et al., 1994; Martin & Jerger, 2005; Westerhausen et al., 2015). Accordingly, evaluation of DL has proved helpful in studying attentional and executive processes in aging (Takio et al., 2009; Westerhausen et al., 2015).

Application of DL in dual-task studies of gait

The use of DL gives several advantages to understand gait changes in aging populations as there exists considerable knowledge on the neuroanatomical mechanisms behind DL. Nonetheless, few studies have applied DL as a cognitive task in a dual-task paradigm. Gadea and coworkers (Gadea et al., 1997) applied it in a manual dual-task, while only two other studies have used it in association with walking (Decker et al., 2017; Gorecka et al., 2018). An important peculiarity of applying DL to dual-task while walking, is that such a situation resembles the daily event in which people walk beside someone else and need to inhibit noise from the environment in order to talk to the near person from one specific side. Thus, we use The Bergen Dichotic Listening Test not only to test how auditory attention disturbs gait, but also to obtain an ecological valid alternative to current dual-task paradigms.

In the past, Decker et al. (2017) used the Bergen Dichotic Listening Task as the cognitive task in a dual-task experiment where young and older participants walked on a treadmill. However, because dual-tasking performed on a treadmill is not equivalent to regular walking (Lazzarini & Kataras, 2016), our group decided to carry out this dual-task paradigm on over-ground conditions. In this way, in 2018 we evaluated how a group of right-handed healthy older adults with varying levels of hearing loss performed DL during walking over-ground (Gorecka et al., 2018). Results showed asymmetrical effects on spatio-temporal measures of gait (i.e., step width, stride length, and gait speed) mainly on the right foot, which were modulated by hearing status. Such alterations occurred when participants focused their attention to the left-ear.

The present study

The above findings are of relevance to better understand how control of focus of attention in the auditory modality affects gait in older persons. Nevertheless, this over-ground experimental procedure has not been assessed with younger individuals. From a developmental perspective, it is important to settle the effects of an experimental situation in individuals at their highest performance capacity, which for most abilities strongly relying on sensory-motor functions is around the second and third decades of life (e.g., Leversen et al., 2012). Therefore, younger people need to be tested in this dual-task paradigm. This will allow us to broader our understanding of the methodology as well as give us a point of comparison for the effects observed in older adults.

For these reasons, in the present study, we aim to investigate possible age-related differences on this dual-task paradigm among right-handed healthy participants. To this end, we will carry out the same methodology as in our previous studies where DL is the concomitant task to over-ground walking. More specifically, we wish to investigate whether there are differences between young and older adults in the cost of the dual-task and on the percent of baseline values across the different DL conditions. Literature in the field suggest that gait parameters of younger adults are not seriously compromised by complex executive tasks, such as the go/no-go task (Beurskens et al., 2016), which could be regarded as equally demanding as the DL task. Thus, it is reasonable to expect that due to the well-functioning of sensory-motor capacities of younger adults, this group would be able to display high performance in the dual-task paradigm. Notwithstanding, the present study is exploratory in nature and DL has not been studied in over-ground conditions among younger adults. Thus, results will answer the question of whether this dual-task paradigm challenges healthy people in the same way regardless of age or whether the observed gait alterations from our previous investigation only arise in older individuals.

Method

Participants

Thirty-six healthy older adults between 63 and 80 years (*M* = 67.11, years, SD = 5.08) and forty younger controls between 19 and 35 years (M = 22.75 years, SD = 2.84) were recruited for the study. All the participants were involved in a larger umbrella project of motor functions and cognition at our institution. All were right-handed volunteers, native Norwegian speakers. Participants were free from any musculoskeletal, neurological, or cardiovascular disease with no walking difficulties, no dementia or cognitive impairment, and no history of depression. In order to control for adequate hearing function, those participants with a hearing threshold of pure tone average (PTA) of >25 dB were excluded. In addition, all participants enrolled in the study scored above 27 points in the The Mini Mental Status Examination – Norwegian version (MMSE-NR; Folstein et al., 1975; Strobel & Engedal, 2008), which ensure the inclusion of persons with normal cognitive status. Likewise, the Beck Depression Inventory II (BDI-II; Beck et al., 1988) was used in order to exclude possible depressive participants, though none of them scored within the ranges of depressive symptoms. Older adults were recruited through advertisements at the local senior citizens' center, flyers, and as well as by means of word of mouth. Younger adults were recruited from the University campus. Written informed consent was obtained from all participants. The study was approved by the local Research Ethics Committee.

Materials

Neuropsychological tests

A battery of tests was used to obtain a complete profile of the cognitive abilities of both age groups which enables to appraise the cognitive capacities of the participants and hence, better understand the results of the dual-task. Thus, the Clock Drawing Test (CDT; Shulman, 2000) was used to examine visuo-constructive abilities. To examine memory, Logical Memory I and II from Wechsler Memory Scale III (Wechsler, 1997) were used. The subtest Digit Span forwards and backwards from WAIS-IV (Wechsler, 2014) were used to examine attention and working memory. The Stroop Word Color Test (Golden, 1978) and Trail Making Test A and B (TMT; Reitan & Wolfson, 1993) were used to examine processing speed and executive functions, like inhibition and cognitive flexibility.

Background variables

Participants were interviewed about their background including education, health and disease, and daily functioning. Participants filled out the following questionnaires for laterality measures: Annett Handedness Inventory (Briggs & Nebes, 1975), and the Waterloo Footedness Inventory (Elias et al., 1998). To assess subjective assessment of physical health each subject responded to the 36 – item Health Survey (SF-36) (Loge et al., 1998; Ware & Sherbourne, 1992).

Audiometric screening

All participants completed audiometric screening using pure tone audiometry (Madsen Itera II, GN Otometrics, Denmark). Hearing sensitivity was measured calculating the Pure Tone Average (PTA) from hearing thresholds of the frequencies 500 Hz, 1000 Hz, 2000 Hz and 4000 Hz. PTA scores above 25 dB as well as an interaural difference larger than 15 dB was used for exclusion of participants.

Gait assessment

Spatio-temporal parameters were acquired using the Optogait System (Optogait, Microgate, Bolzano, Italy). The system quantifies gait parameters using photoelectric cells that register interference in light signals. The sensors in the Optogait system are placed over ground creating a seven meter long x 1.3 meter wide rectangular corridor where subjects walk in loops counter-clockwise. Ninety-six LED diodes are positioned on each bar one centimeter apart at three millimeters above the ground. When subjects pass between two bars positioned in parallel with the ground, transmission and reception are blocked by their feet. Timing, size, and distance are sensed, and spatio-temporal parameters are automatically calculated. Data were extracted at 1,000 Hz and saved on a PC using OptoGait Version 1.6.4.0 software. Gait parameters examined were gait speed, step length, and step width, for both feet (i.e., bilateral) and by foot. Variability was calculated for each parameter using coefficient of variability (CoV). All walking conditions were recorded with two Logitech web cameras from different angles to overlook any difficulties or changes during walking condition. The Optogait system has proved to be a highly reliable and valid instrument (Lee et al., 2014; Lienhard et al., 2013).

Dichotic Listening task

We applied the Bergen Dichotic Listening Test (Hugdahl & Andersson, 1986). The paradigm consists of six consonant-vowel (CV) presentations:/ba//ta//pa//ga//da//ka/where different CVs were presented simultaneously and randomized, each syllable of 350 milliseconds duration. The syllables were paired with each other in all possible combinations to form 36 different syllable pairs. From these, six homonyms pairs (e.g., ba–ba) were included in the test as perceptual control. The CVs were read by a Norwegian-speaking male voice with constant intonation and intensity with a time interval of 4000 milliseconds. The total duration of each DL condition was three minutes. DL-responses were recorded with a digital voice recorder hanging around the participants' neck. The syllables were presented using wireless noise-canceling headphones. E-prime 2.0 Software (Psychology Software Tools, Inc., Pittsburgh, PA, USA) was used to present the stimuli. The DL procedure has three conditions: The Non-Forced condition (NF) was always performed first, where participants were instructed to report the syllable they heard the clearest. For the following conditions, participants were instructed to pay attention and loudly report stimuli from either right (Forced-Right, FR) or left (Forced-Left, FL) side, while ignoring information from the opposite ear. The order of the FR and FL were counterbalanced across subjects depending on their ID number.

Procedure

The study took place at Department of Psychology, UiT Arctic University of Norway. Participants were interviewed initially to acquire their demographic background and health history. Afterward, all subjects underwent audiometric screening and neuropsychological testing in a sound-attenuated room. The dual-task experiment was conducted in a rectangular-shaped, sound-attenuated room. Participants walked within the Optogait system in a self-selected, comfortable walking speed counter-clockwise. The experimenter showed beforehand the direction of walking within the assigned area. The Optogait system started recording gait as the subject took the first footstep, initiated by a verbal signal. In the baseline condition, participants were asked to walk for one minute within the corridor. Baseline-condition was shorter than the rest of the dual-task conditions to assure that subjects did not get tired or lightheaded while allowing acquisition of enough gait data to obtain spatio-temporal parameters in the control condition. Prior to dual-task conditions, participants were given a demonstration trial of the experimental procedure. Also, participants were required to listen and respond to three CV-presentations while wearing headphones without walking, to ensure comprehension of the instructions. In the dual-task condition, subjects were asked to walk continuously and execute the DL task as accurate as possible. The instructions given were: "We ask you to say loudly the syllables that you perceived a) the clearest (in Non-Forced condition), b) from right-ear (in Forced-Right condition), c) from left-ear (in Forced-Left condition), while you walk in rounds in the designated area as previously demonstrated. Please keep walking and reporting the syllables during the entire trial as well as you can". It is important to highlight that the experimental situation did not open for any beforehand task prioritization, but rather instructions denote equal prioritization for both tasks. The dichotic stimuli was initiated simultaneously as the subject lifted a foot to initiate walking, again when the experimenter gave a verbal cue. Finally, careful adjustment of the volume was ensured for each person. Data acquisition for gait parameters in the present study were aggregated scores based on the 1-minute trial for baseline and on each 3-minute trial of the three DL conditions. Short breaks were given between conditions. The oral responses were recorded and written down by one experimenter. Afterward, the recorded responses were listened and manually inserted in the E-prime software by a second experimenter, which ensure reliable data. Laterality indexes and correct responses were calculated by the DL software. Duration of test session was approximately two hours.

Statistical analyses

All analyses were performed with the statistical package IBM SPSS Statistics 26 for Windows (IBM Corp., Armonk, N.Y., USA). Group comparisons for demographics, background variables, cognitive tests and questionnaires were performed with independent t-tests. The assessment of the effects of DL on gait was conducted through two approaches. First, we analyzed the absolute differences in raw scores by calculating dual-task cost scores (DTCs) on the mean (DTCM) and CoV (DTCCoV) of all spatiotemporal parameters. DTCs were calculated by determining the difference between gait parameters in single walking and gait parameters during the three dual-task conditions (e.g., gait scores in Baseline *minus* gait scores in NF, FR and FL). Then, DTC scores were used in statistical analyses. This first approach relying on the use of DTCs allows for a straightforward understanding of the effects of the experimental situation in *raw scores*, which is important for clinical application (Baker et al., 2009). The second approach adopted for the analysis of group differences was based on the evaluation of "percent of baseline values", which allows for group comparisons on the proportion of performance affected by the DL conditions. Percent of baseline values were calculated by dividing each gait parameter obtained under each DL condition by baseline gait scores and multiplied by 100, e.g.:

$$\text{Percent of baseline gait speed in NFcondition} = \frac{\text{gait speed in NFcondition}}{\text{gait speed in baseline}} X100$$

A series of factorial analyses of variance with repeated measures in one factor were carried out to assess DL, DTCs, and percent of baseline values. For DL, we had the Group (Young, Old) as between-subjects factor while Ear (right, left) and Condition (NF, FR, FL) were the within-subjects factors. For gait data, the Group (Young, Old) was the between-subjects factor while Foot (right, left) and Condition (NF vs Baseline, FR vs Baseline, FL vs Baseline) were the within-subjects factors. In case of a significant omnibus test, univariate tests were performed. In case of significant interactions, analyses for simple main effects were carried out. For gait, we analyzed the mean and CoV separately by gait parameter as both descriptors are important to evaluate in linear measures of gait outcomes (Hamacher et al., 2011). Also, we analyzed first bilateral outcomes and then lateralized outcomes. Since asymmetries were found among older adults in our previous study (Gorecka et al., 2018), we adopted this approach to investigate possible asymmetric effects on gait parameters by DL condition. In all analyses, Greenhouse-Geisser corrections were chosen when the sphericity assumption was not met. Significant interactions or main effects involving group differences were followed up with appropriate post-hoc analyses. Due to multiple comparisons across all factorial ANOVAs, the Bonferroni correction was applied.

Statistical analyses for supplementary material

Finally, for a better appraisal of the findings reported in this study, we present raw scores for bilateral and lateralized gait outcomes as supplementary material. These data were analyzed with a set of mixed repeated measures ANOVAs using the design 4 x Condition (Baseline, NF, FR, FL) as the within-subjects factor x 2 Group (Young, Old) as the between-subjects factor. Thereafter, and in accordance with our earlier study (Gorecka et al., 2018) we conducted a series of ANCOVAs on these raw data that corrected for hearing status. The reason for focusing on hearing loss relates to various important aspects of our study. To begin with, the sensory modality of the concomitant cognitive task (DL) is hearing and older adults over 60 years of age show substantial hearing loss that need to be taken into account (Bush et al., 2015). Second, age-related hearing loss affects greatly balance and walking in the older adult (Lin et al., 2011) and third, hearing loss is tightly related to cognitive deficiencies in aging (Dupuis et al., 2015). Based on the above, "pure tone averages" (PTA) of the frequencies 500, 1000, 2000 and 4000 Hz were calculated and used as covariate in the gait analyses presented in Supplementary material.

Results

Results from demographic variables are shown in Table 1. As commonly reported, young adults had significantly more years of education than older adults. Positive measures from the Handedness Inventory and Footedness Inventory confirmed that both the old and young participants had a preference for right hand. However, we found significant group differences only on the Handedness Inventory where older adults reported to prefer the use of right hand significantly more than younger adults. No group differences were found in terms of self-reported health status or depression.

Table 1. Demographics and subjective assessments of hand and foot preference, depression scores and health status.

	Young adults (N = 40)	Older adults (N = 36)	
	14/26	10/26	
Gender (men/women)	*M (SD)*	*M (SD)*	*t*
Age	22.81(2.86)	67.11(5.09)	
Education (years)	15.40 (2.27)	13.59 (2.27)	2.77*
BDI-II	5.36 (5.84)	5.11 (4.31)	0.21
Handedness	16.63(12.25)	21.06 (3.71)	−2.08*
Footedness	7.88 (9.15)	10.86(7.72)	−1.51
SF-36	106.27 (6.68)	103.69 (6.87)	1.61

M = mean, *SD* = standard deviation (* $p < .05$). BDI-II = Becks Depression Inventory. SF-36 = Short Form Survey 36 items

Table 2. Means and standard deviations from neuropsychological tests.

	Young (*N* = 40)		Old (*N* = 36)		
Measure	*M (SD)*		*M (SD)*		*t*
MMSE-NR	29.28	(1.43)	28.92	(1.46)	1.8
CDT	6.95	(0.22)	6.81	(0.57)	1.5
TMT A	25.30	(8.2)	35.50	(17.70)	−3.28*
TMT B	65.07	(23.45)	80.04	(27.50)	−2.55*
Stroop W	107.38	(15.00)	89.08	(18.27)	4.58***
Stroop C	86.83	(11.73)	62.19	(12.06)	8.99***
Stroop WCI	59.73	(13.68)	33.83	(8.06)	9.90***
DigitSpan F	9.78	(2.14)	9.08	(2.06)	1.55
DigitSPan B	8.90	(1.65)	8.25	(2.13)	1.43
Log Mem I	11.54	(4.09)	11.36	(3.10)	.21
Log Mem II	10.54	(4.28)	15.22	(3.49)	−5.16**

M = Mean, *SD* = Standard deviation. MMSE-NR = Mini Mental Status Examination Norwegian Version. CDT = Clock Drawing Test. TMT = Trail Making Test. Stroop W = Stroop Word, Stroop C = Stroop Color, Stroop WCI = Stroop Word-Color Interference, DigitSpan F = Digit span forwards, DigitSpan B. Log Mem = Logical memory. (* $p < .05$, ** $p < .01$, *** $p < .001$)

Neuropsychological scores

Results from neuropsychological assessments are displayed in Table 2. Older adults presented significantly lower performance than the younger group on TMT A and B, as well as on all Stroop conditions. In addition, older adults recalled less information on delayed memory measures.

Hearing Thresholds

Table 3 shows hearing thresholds interaurally for both groups. As portrayed, all PTA scores were below 25 dB. Though, older adults had significantly higher hearing thresholds as compared to younger adults across all outcomes. Worst-PTA indicates actual auditory dysfunction, while best-PTA shows auditory compensation (Linssen et al., 2014).

Dichotic listening results. Three-way MANOVA showed a statistical significant main effect for Ear (F [1,74] = 60.81, p <.001, $\eta 2_p$ = 0.45) and Group (F [1,74] = 9.59, $p < .01$, $\eta 2_p$ = 0.12). No significant effect was seen for Condition. There was also a significant interaction effect between Condition x Ear, naturally due to the change in focus of attention driven by the instructions, which was expected, (F [2,73] = 17.99, $p < .001$, $\eta 2_p = 0.33$). However, the results showed a significant interaction effect of Condition x Group (F [2,73] = 3.76 $p < .05$, $\eta 2_p = 0.09$), indicating significant differences between older adults and young adults on some of the DL conditions. Post hoc analysis showed no significant group difference in right ear responses in any of the three conditions (see Figure 1). However, a significant group difference for correct responses from the left ear was seen in FL condition (F [1,74] = 8.38, $p < .05$, $\eta 2_p$ = 0.10, see Figure 2). The younger adults showed a REA in NF and FR and a *left-ear advantage* (LEA) in FL. In contrast, older adults showed REA in all three conditions.

Since hearing acuity differed signficantly between groups and this condition affects the perceptual ability of older participants as well as their cognitive abilities (Bush et al., 2015), we decided to control for hearing differences by conducting a factorial MANCOVA. Thus, worst-PTA, e.g., highest threshold in hearing acuity, was entered as a covariate to evaluate whether auditory deterioration influenced the observed group differences. In fact, results showed that when controlling for worst-PTA, the interaction effect on NF was no longer present (F [2,72] = 1.08, p = NS, $\eta 2_p$ = 0.02). However, the

Table 3. Mean and standard deviations for hearing thresholds in decibels (dB).

	Young (*N* = 40)	Old (*N* = 36)	
	M (SD)	*M (SD)*	*t*
PTA Right	8.09 (3.95)	14.81 (4.73)	−6.8***
PTA Left	7.03 (5.01)	14.98 (4.13)	−7.41***
PTA Best	5.85 (4.03)	13.59 (4.15)	−8.23***
PTA Worst	9.26 (4.47)	16.19 (4.32)	−6.86***

PTA = Pure Tone Average. PTA Best = Lowest threshold for both ears. PTA Worst = Highest threshold for both ears (*** $p < .001$)

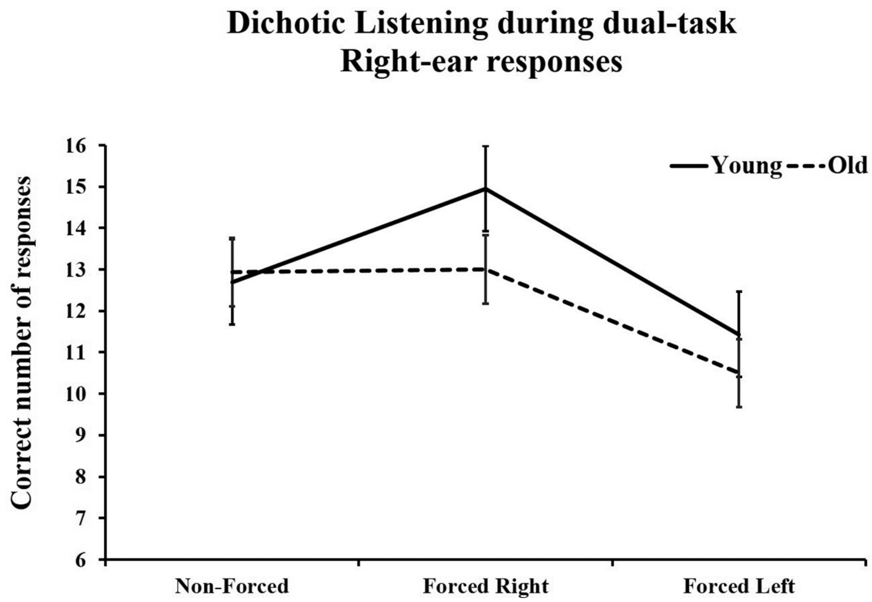

Figure 1. Mean and ± SEM for correct right-ear responses across three dichotic listening conditions.

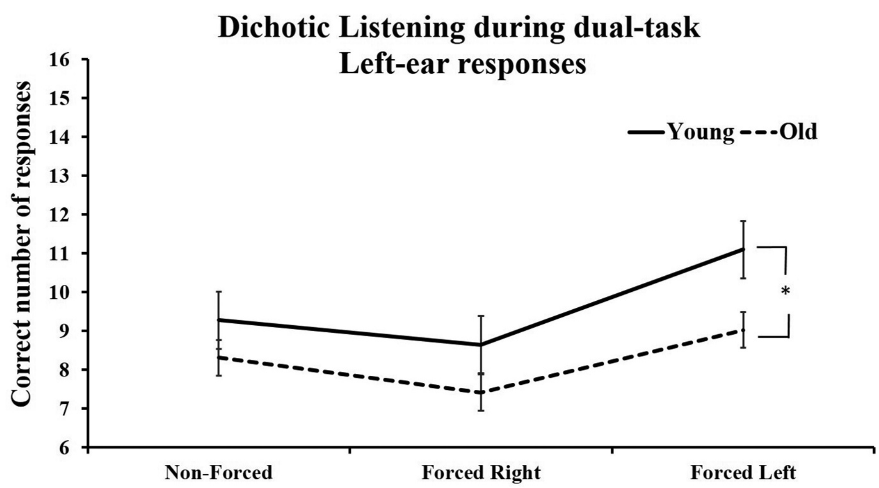

Figure 2. Mean and ± SEM for correct left-ear responses across three dichotic listening conditions. (* p <.05).

group differences were still present F [1,73] = 3.92, p < 0.05, $\eta2_p$ = 0.05). Post Hoc analysis showed a trend toward older adults reporting less from the left side in the FL condition (p = NS). In summary, variation in hearing acuity played a significant role in the performance of DL executed while walking.

Gait Although, the focus of all analyses in this study is on the DTCs and percent of baseline values, the bilateral raw data for gait parameters are also reported in the Supplementary Material. We highlight that results for DTCM, DTCCoV and percent of baseline values for bilateral (i.e., right and left-foot data together) outcomes and outcomes by foot (i.e., right-foot vs left-foot) were calculated and analyzed separately.

Bilateral results DTCM

Two-way MANOVA showed only a significant main effect of Condition for DTCM gait speed (F [2,73] = 12.43, p < .001, $\eta2_p$ = 0.25, see Figure 3) and DTCM step length (F [2,73] = 11.130, p < .0001, $\eta2_p$ = 0.20, see Figure 4). Additionally, a main effect for Group (F [1,74] = 43.23, p < .0001, $\eta2_p$ = 0.36) was also found in DTCM step length (see Figure 4). No significant main effects or interactions were found for DTCM step width.

Bilateral results for DTCCoV

For bilateral variability data we did not find any significant effect or interaction in any of the gait parameters.

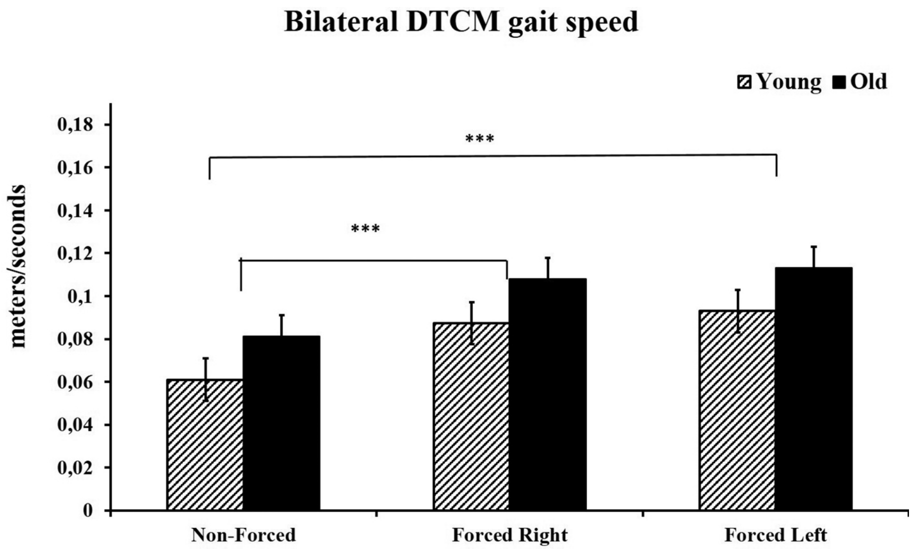

Figure 3. Mean and ± SEM for DTCM for gait speed. DTCM = Dual-task costs of mean values for bilateral outcomes (m/s). *** = $p < .001$.

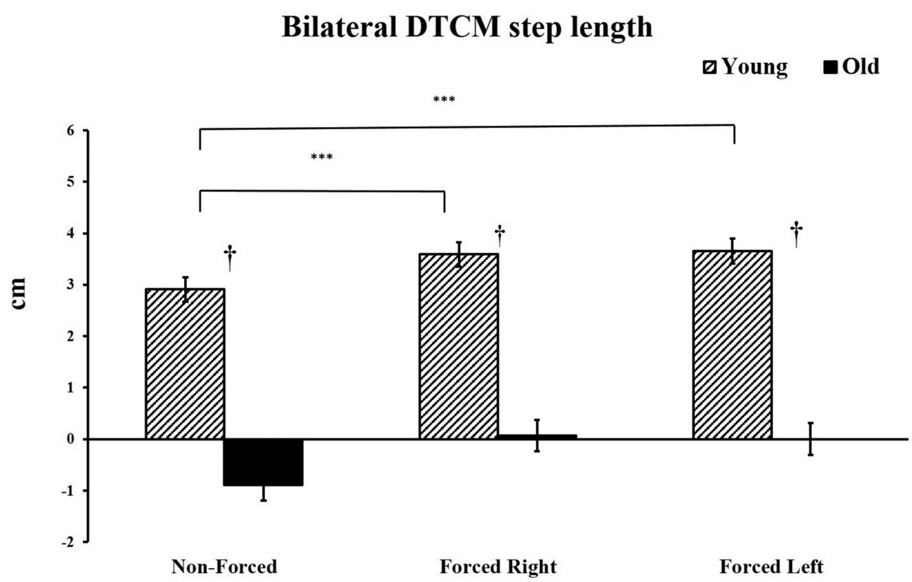

Figure 4. Mean and ± SEM for DTCM for step length. DTCM = dual-task costs of mean values for bilateral outcomes. *** $p < .001$ significant differences between conditions. † $p < .001$ significant differences between groups.

Lateralized results for DTCM

Not surprisingly, lateralized data showed similar results as in the bilateral outcomes. This regards gait speed, in which only a main effect of Condition was found (F [2,73] = 10.50, $p < .001$, $\eta 2_p = 0.22$). As in the bilateral data, the change from baseline to NF on both right and left feet was significantly lower than the cost of the dual-task in the FR and FL conditions. However, on step length we found a main effect of Group (F [1,74] = 30.79, $p < .001$, $\eta 2_p = 0.29$, see Figure 5) where younger adults displayed larger costs of the dual-tasks condition than older adults. No significant findings were found for step width.

Lateralized results for DTCCoV

As in the bilateral data, there were no significant findings for gait speed DTCCoV or step width DTCCoV. Though, step length DTCCoV showed a significant interaction between Foot and Group (F [1,74] = 7.78, $p < .001$, $\eta 2_p = 0.10$). Analyses of simple main effects demonstrated the existence of a change in variability in the young group. As depicted in Figure 6, the variability in the younger participants increased significantly on their left foot during the Forced Right condition (F [1,74] = 11.65, $p < .001$ $\eta 2_p = 0.14$, see Figure 6).

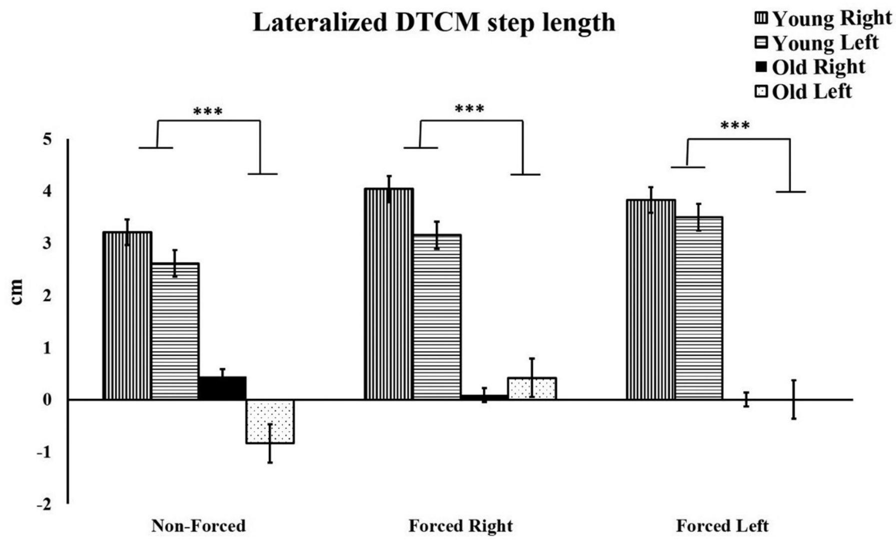

Figure 5. Mean and ± SEM for DTCM for step length by foot. DTCM = dual-task costs of mean values. *** *p* <.001 *Note*: Right/left denote right foot and left foot.

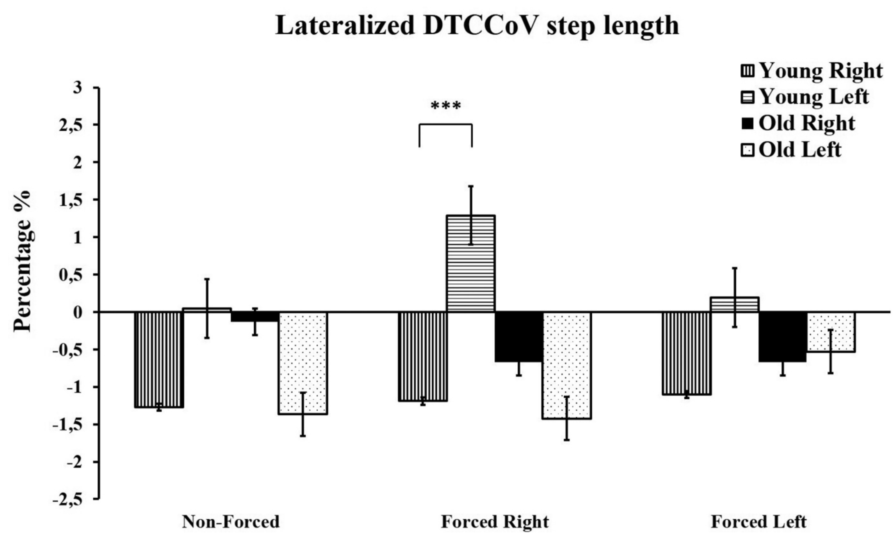

Figure 6. Mean and ± SEM for DTCCoV for step length by foot. COV = coefficient of variation; DTCCoV = Dual-task costs of coefficient of variation. *** = *p* <.001. Right/left denote right foot and left foot. Negative values indicate increased variability and positive values indicate decreased variability

Bilateral results for percent of baseline values

Mean: From these analyses, only the percent of baseline values of the mean for step length showed a main effect of Condition (F [2,73] = 8.58, $p < .0001$, $\eta 2_p = 0.19$) and a main effect of Group (F [1,74] = 44.2, $p < .0001$, $\eta 2_p = 0.37$). The group difference is denoted by the preserved ability of older adults in step length across DL conditions, while the younger group had a reduction of almost 5% across DL conditions. Specifically, the proportion of step length execution was mostly reduced in younger adults during the conditions where voluntary control of attention was required (FR and FL conditions). In addition, we also found a main effect of Condition for the percent of baseline values of the mean for gait speed (F [2,73] = 13.35, $p < .0001$, $\eta 2_p = 0.27$). No further significant findings were obtained for the percent of baseline values of the mean for step width, see Table 4.

CoV: In these analyses we obtained a main effect of Group in the percent of baseline values of CoVs for step length (F [1,74] = 8.09, $p < .006$, $\eta 2_p = 0.10$) and gait speed (F [1,74] = 7.38, $p < .008$, $\eta 2_p = 0.09$). In the former, it was observed that older participants incremented their step length variability by 27% in the NF-condition as compared to baseline, while the increment for the FR and FL-conditions was of 36%. In contrast, the younger group basically preserved their step length variability across DL conditions. As for gait speed variability, we found that older adults augmented this feature by 53.7% in the NF-condition, while their increment for FR-condition was of 67.2% and of 89.5% in the FL-condition. The younger group once more showed rather a preservation of their gait speed variability across DL conditions as compared to baseline, see Table 4.

Lateralized results for percent of baseline values

Mean: These analyses showed one significant main effect of Condition for the percent of baseline values of the mean for gait speed (F [2,73] = 12.09, p < .0001, $\eta 2_p$ = 0.25). A reduction in performance of 6–7% occurred in the NF-condition, which was further reduced by 10% in the directed attention conditions FR and FL in both groups. Additionally, a significant main effect of Group on the percent of baseline values for the mean of step length was found (F [2,73] = 12.09, p < .0001, $\eta 2_p$ = 0.25). This finding replicates in much the data obtained in the bilateral analyses where the older group showed preserved execution and the younger group had decreased performance across all DL conditions, see Table 5.

CoV: In these analyses we only obtained a significant main effect of Group for the percent of baseline values for the CoV of step length (F [1,74] = 8.76, p < .004, $\eta 2_p$ = 0.11). Even though no significant interaction was observed, it was clear that some of the older adults increased their step length variability of their left foot by almost 50% and, as observed in the bilateral analyses, this group demonstrated

Table 4. Average percent of baseline by DL condition for bilateral gait parameters.

	CONDITION								
	Non-Forced		Forced-Right		Forced-Left				
	Young	Old	Young	Old	Young	Old	RMANOVA, *p-value*, *(η2p)*		
	M (SD)	*M (SD)*	*M (SD)*	*M (SD)*	*M (SD)*	*M (SD)*	Condition/Interaction/Group		
Mean									
Step length%	95.3 (4.5)	101.4 (3.3)	94.2 (5.7)	99.9 (2.3)	94.0 (5.8)	100.0 (0.0)	0.001 (0.19)	/NS	/0.001 (0.34)
Gait speed %	93.4 (8.2)	92.9 (9.1)	90.4 (11.2)	90.7 (9.5)	89.7 (11.2)	90.1 (8.7)	0.001 (0.26)	/NS	/NS
Step width%	100.1 (22.7)	119.9 (100.3)	100.0 (21.3)	116.9 (92.9)	104.2 (24.4)	125.1 (103.7)	0.02 (0.10)	/NS	/NS
CoV									
Step length%	104.8 (16.3)	127.5 (64.6)	101.4 (16.6)	136.1 (79.0)	104.2 (16.4)	136.5 (77.1)	NS	/NS	/.006 (0.1)
Gait speed%	106.1 (36.9)	153.7 (133.9)	101.9 (21.8)	167.2 (194.1)	100.6 (12.8)	189.5 (231.2)	NS	/NS	/.008 (0.09)
Step width%	101.0 (0.2)	101.0 (0.3)	101.1 (0.2)	101.1 (0.5)	101.0 (0.2)	101.0 (0.1)	NS	/NS	/NS

Abbreviations: *M* = mean; *SD* = standard deviation; RMANOVA = repeated measures multiple analysis of variance; CoV = Coefficient of Variation; Interac. = Interactions; NS = Non Significant. CoV = Calculated with the formula: [mean/SD] x 100%

Table 5. Average percent of baseline by DL condition for lateralized gait parameters (by foot).

	CONDITIONS									
	Non-Forced		Forced-Right		Forced-Left					
	Young	Old	Young	Old	Young	Old	Two-way ANOVA, *p-value*, (η2p)			
	M (SD)	M (SD)	M (SD)	M (SD)	M (SD)	M (SD)	Condition/Foot/Interaction/Group			
Mean										
Step length R%	94.8 (4.0)	99.0 (15.8)	93.5 (5.9)	99.8 (2.6)	93.8 (5.7)	100.0 (0.0)				
Step length L%	95.8 (5.3)	101.3 (3.4)	94.9 (5.9)	99.9 (2.4)	94.3 (6.2)	100.0 (0.0)	NS/	NS/	NS/	0.0001 (0.29)
Gait speed R%	93.4 (8.3)	94.8 (12.9)	90.7 (11.1)	90.7 (9.6)	90.1 (11.4)	90.1 (8.6)				
Gait speed L%	93.2 (8.7)	93.0 (9.2)	90.4 (11.4)	90.7 (9.5)	89.4 (11.6)	90.1 (9.0)	0.001 (0.25)/	NS/	NS/	NS
Step width R%	101.3 (28.5)	95.3 (141.4)	102.3 (28.4)	102.6 (114.8)	106.0 (33.9)	113.4 (127.3)				
Step width L%	101.6 (25.1)	126.0 (97.2)	101.4 (27.4)	126.4 (98.9)	105.8 (24.3)	130.7 (106.4)	NS/	NS/	NS/	NS
CoV										
Step length R%	111.1 (26.6)	110.5 (41.4)	111.2 (29.5)	126.8 (74.7)	109.7 (24.1)	131.7 (74.2)				
Step length L%	103.5 (25.1)	149.0 (98.3)	95.8 (21.1)	151.7 (101.5)	103.2 (25.8)	151.4 (95.9)	NS/	NS/	NS/	0.004 (0.10)
Gait speed R%	102.5 (17.2)	161.5 (171.1)	101.0 (16.11)	162.2 (204.8)	100.2 (13.4)	208.7 (291.3)				
Gait speed L%	107.6 (48.2)	160.1 (124.6)	102.2 (28.4)	177.7 (245.0)	100.7 (15.5)	193.4 (272.5)	NS/	NS/	NS/	NS
Step width R%	101.0 (0.2)	101.0 (0.3)	101.0 (0.22)	101.1 (0.5)	101.0 (0.2)	101.0 (0.1)				
Step width L%	101.0 (0.2)	101.0 (0.3)	101.0 (0.2)	101.2 (0.5)	101.0 (0.2)	101.0 (0.1)	NS/	NS/	NS/	NS

Abbreviations: *M* = mean; *SD* = standard deviation; CoV = Coefficient of Variation; Interac. = Interactions; NS = Non Significant. CoV = Calculated with the formula: [mean/SD] x 100%

a marked increment in variability across all DL-conditions. The younger group showed a higher increment in step length variability on their right foot, especially in the NF and FR-conditions, see Table 5.

Discussion

Effects on gait

DTC findings. The present study aimed to assess whether age-related differences existed in dual-tasking when DL was performed simultaneously during overground walking. As a whole, our findings demonstrated similar results in both younger and older adults. For instance, both groups showed larger DTCMs in gait speed and step length across all three DL conditions. Interestingly, this dual-task paradigm did not affect step width in any of the groups. Now, the DL conditions affected differently DTCM scores in both groups being the NF the one that less impacted gait. In contrast, FR and FL were more challenging as under these two conditions participants presented greater DTCs on speed and step lengths than during the NF condition.

Even though the dual-task paradigm affected gait parameters in both groups in almost the same way, there was an important age-related difference. We found that younger participants were more affected than older adults on their step length DTCM and more remarkably on the DTCCoV of the same gait parameter, as it displayed a significant lateralized difference on left foot. The bilateral data suggest that younger persons had to adjust their step length mean more during FR and FL conditions. In addition, the younger group showed a significant change on the lateralized DTCCoV scores for their left foot, which reflects a noteworthy capacity for diminished variability. To understand these results we refer to the standard interpretation of DTC scores, where negative values reflect worsened performance on dual-tasking relative to single-tasking and positive values reflect improved execution under dual-task conditions (Plummer & Eskes, 2015). Based on the above, our data indicate that younger adults are able to better regulate step length variability of their left foot when they attend to right-ear stimuli during FR condition.

Let us remind that in right-handed persons, reporting stimuli from right-ear is expected to be less effortful than reporting from left-ear (Hugdal & Westerhausen, 2016). Hence, the FR experimental situation may allow younger participants to improve their gait in order to cope with the task's demands. In the literature, it is most common to encounter that older adults show major changes in gait variability than younger people, particularly in demanding situations. However, there are data pointing to changes in variability in healthy younger adults since a certain degree of gait variability reflects a healthy organism (Hollman et al., 2016). For example, Plotnik and colleagues (Plotnik et al., 2013) showed that bilateral coordination was affected in young adults while walking slowly but not in fast walking. In line with these findings, Almarwani and coworkers (Almarwani et al., 2016) also showed that either slower or faster walking affected in a very peculiar way step variability of younger participants. These authors reported that such a change was not observed in older adults under the same conditions. Interpretation of these findings was that slower walking exerts challenges in younger people as it reduces gait automaticity and imposes higher cortical control to regulate muscular activity (Almarwani et al., 2016).

The above reports are relevant to the present study since our younger group indeed walked at a slower pace across DL conditions (see raw data in Supplementary Material). At the same time, younger participants showed their best performance for DL during the FR condition where they correctly report the highest number of correct stimuli. Taken together, it seems that younger adults recruited their available resources in FR condition to compensate for demands on walking by reducing step length variability on their left foot. This finding brings up the matter of gait asymmetries in healthy populations. Even if gait asymmetry has been usually linked to pathological states (Yogev et al., 2007; Yogev-Seligmann et al., 2008), reports about normal gait asymmetries are not uncommon in healthy people. A review by Sadeghi and colleagues (Sadeghi et al., 2000) suggests that asymmetries in healthy people raised as a natural differentiation of function between the limbs and reflect compensatory abilities. In particular, these authors proposed that the role of right-limb is that of propulsion, while the role of the left-limb is of support. Therefore, we interpret our data as an indication that younger adults are able to better control their ability for support as a compensatory process. One speculative explanation to this finding, would be that shared neural demands between both brain hemispheres exist during focusing to right-ear while walking. Roughly, the literature in laterality proposes that right-brain hemisphere specializes in language while the left-brain hemisphere specializes in non-verbal information, somatosensory and spatial functions (Zaidel, 2001). Therefore, it is possible that the findings observed in the young group are due to left-brain hemisphere handling automatic attentional focus of right-ear information, while right-brain hemisphere is modulating the contralateral side of the body to decrease step length variability and augment the support during walking. Clearly, our data cannot unveil the neural causes behind gait asymmetries in healthy people. Still, what is evident is that gait asymmetries arise in individuals without clinical conditions depending on task demands (Sadeghi et al., 2000). Our previous study with healthy older adults demonstrates this issue (Gorecka et al., 2018). Thus, the present results only corroborate that our dual-task paradigm causes asymmetric gait changes in older and younger participants, albeit not of the same nature. In older adults, there are mixed changes reflecting both deleterious effects as well as compensatory outcomes. In the present study, the asymmetric effect found in younger adults seems to be compensatory as it improves and stabilizes walking in the dual-task context.

The proportion of adjustments across DL conditions between groups: Percent of baseline findings. Complementary to the DTC results are the group differences observed on the percent of baseline values, which allow for a different comparison across groups of retained, reduced or gained performance relative to baseline execution. These data point to the magnitude of adjustments occurring on a specific outcome and condition as compared to baseline. The most important result from these analyses regards again the step length data. We obtained group differences in the mean and CoV of percent of baseline values of step length in both the bilateral and the lateralized results. The findings indicate that for the mean, older adults preserve their ability of step length better than the younger group who had a reduction of almost 5% across DL conditions, especially during the FR and FL conditions. Nevertheless, the results from the lateralized analyses showed that the older group presented important variations in step length variability that were not present in the younger group. These data agrees with a large body of literature pointing to increase step length variability in older persons (Brach et al., 2001). The bilateral results showed an increment of 27% in the NF-condition as compared to baseline and of 36% in the directed attention conditions for the older adults, while younger participants mainly preserved their same step length variability across conditions. Additionally, the lateralized results are noteworthy in spite of the lack of significant interactions denoting asymmetries. The figures presented in Table 5 suggest the existence of important asymmetric alterations on the step length variability in *some* of the participants in both groups. This state of affairs is most noticeable for the older group. Essentially, our data document that in agreement with a vast literature (e.g., Smith et al., 2016) older persons experience a deleterious effect of performing a complex dual-task paradigm. In this case, older individuals had an increment on their step length variability of almost 50% in all conditions, being more prominently for their left foot. It is broadly acknowledged that increase step length variability is related to increased risk of falling and a sign of deleterious perturbations on gait (Rosso et al., 2014). Thus, our data confirm that older persons are more challenged from the experimental situation than younger adults are, as the younger showed an increase of variability of not more that 10% across conditions. Nevertheless, and again in spite of significant interactions, the data suggest that younger participants experience a lateralized effect on step length variability that occurred in the FR condition.

Understanding DTC findings and percent of baseline results

In the present study, we decided to employ two approaches to investigate the effects of DL during over-ground walking. The first approach regarded the evaluation of DTCs on raw scores of gait parameters, while the second approach considered the evaluation of gait modifications in percent of performance relative to baseline execution. These two approaches are important and complementary. The first approach considers dual-task effects directly on untransformed raw scores of gait, which is a strategy recommended in the gait literature for an easier interpretation and clinical usage (Baker et al., 2009). The second approach allows for a comparison between groups in terms of magnitude of effects relative to baseline due to dual-tasking. Thus, taking together information from both approaches, it is evident that the most important alteration caused by executing DL during over-ground walking is on step length variability in both groups. However, the effects are quite different. As already explained in the previous section, the younger group had a decrement of DTCCoVs on left foot that is on the "support action" during walking. These decrements on variability need to be understood as a strategy of the young group to preserve a safe walk. Thus, while DTC data demonstrate this decrement, the percent of baseline values showed a slight increment in step length variability of the younger group's right foot, which implicates that our dual-task environment is a challenging one even for young persons in their best functional years. Concerning the older group, results from DTCs suggested little effects on their mean and CoV of step length in terms of differences across conditions in raw data. However, the percent of baseline results demonstrated that older participants actually undergo deleterious effects by performing our dual-task situation, as they have a remarkable increment in step length variability when compared to the younger participants. These findings point to an increased risk of falling (Young & Dingwell, 2012) when attending auditory stimuli while walking. All in all, the present results confirm our hypothesis that that younger persons are more prone to adapt appropriately to the dual-task situation created by DL task as this group is able to adjust their step length advantageously.

Effects on dichotic listening in relationship with neuropsychological performance

Overall results of the DL data demonstrated that younger adults showed appropriate ability to control their attention to the right or left ear, respectively, during the FR and FL conditions. They also demonstrated a clear REA during the NF condition. Conversely, the older participants showed an overall lower execution and a clear REA in all three conditions. Interestingly, the interaction observed on the FL condition where the older group had a greater difficulty to report from left-ear, disappeared after controlling for hearing status. This finding suggests that sensory loss in the auditory modality moderates exacerbated group differences in DL. However, controlling for hearing loss did not remove the main effect of group across conditions, which indicates that age differences on DL are related to normal cognitive deterioration occurring in healthy aging, such as declined executive functioning in shifting, mental flexibility, and response inhibition (Hommet et al., 2010; Hugdahl et al., 2009).

The latter statement is substantiated by results of the cognitive battery in our study, where younger adults outperformed significantly older participants on measures of executive functions and cognitive flexibility, such as the Stroop Color/Word interference task and TMT B. In addition, another significant group difference was obtained on measures of processing speed where older adults showed enlarged time to perform a task (i.e., TMT A) or limited abilities due to time restrictions (i.e., Stroop word reading and color naming). The observed age-related declines in executive function and processing speed explain group differences encountered in DL since both cognitive domains are needed to select and inhibit auditory stimuli form right or left-side during relative short intervals. It is possible that the dual-task context contributed to a more difficult environment to perform the DL conditions. Though, this situation seemed to affect both groups in the same way as group differences were constant and they agree with findings from single-task DL studies (Andersson et al., 2008; Bouma & Gootjes, 2011).

In the past, authors have suggested that poor executive function/attention and processing speed are associated with many aspects of gait decrements, and that the involvement of executive functions becomes stronger when the walking task is more challenging (Hobert et al., 2017; Martin et al., 2013; Yogev-Seligmann et al., 2008). Thus, our conjoined data from the test battery and DL task reveal that the sample of older adults displayed normal cognitive deficits on executive functions and processing speed, which explain why they had higher DTCs on the conditions where "top-down" control was required, namely on the FR and FL conditions. In sum, these results stress the importance of applying a thorough neuropsychological evaluation in dual-task studies in order to disentangle the reciprocal effects of the dual-task situation on cognition and gait.

Limitations of the study

Creating a new methodology, such as the use of DL during walking, implicates the emergence of unforeseen issues. Therefore, several limitations need to be acknowledged in the present investigation. To begin with, the lack of a single-task for DL where participants only perform the cognitive task in a sitting position is a limitation. On one hand, we wanted to evaluate the effects of the experimental situation without previous exposition to DL, and therefore, we intentionally did not assess DL as a single task. This solution is frequent in dual-task studies. For instance, the majority of the studies reported on the meta-analysis by Al-Yahya et al. (2011) did not assess single-task performances in cognition. The rationale of avoiding single-execution of DL was important to appraise the effects of this over-ground dual-task paradigm as a novelty situation. On the other hand, since the present study was part of a larger umbrella project of motor functions and cognition, the number of tasks necessary for each part of the investigation were thoroughly weighted by the ethical review board. Our argumentation about not applying DL as a single-task, was valued by the committee, especially since the research aimed to understand the effects of an ecological valid design that was not relying in previous exposition to the cognitive task. However, we acknowledge that future research should evaluate the effects on gait and cognition when participants have previous experience on DL as single-task. Since the dichotic listening task employed in this experiment is assumed not to have training effects, especially on populations who fail to show a left-ear advantage during FL condition (Hugdahl et al., 2009), the inclusion of single-task DL would allow for calculation of DTCs on all conditions.

Another potential limitation is that our subjects were not instructed to prioritize any task in this dual-task experiment. In the absence of specific instructions about which task needs to be prioritized, subjects tend to allocate attention to their gait at the expense of the cognitive test, which is a "posture-first" strategy (Shumway-Cook et al., 1997). In our study, the instructions were to perform as well as possible the DL task and walking simultaneously, which implies an equal prioritization. Nevertheless, each single participant might have prioritized differently. Further studies with our dual-task paradigm need to control for the effects of task instructions. However, we need to keep in mind that effects of task prioritization are not similar for younger and older adults (Bayot et al., 2018), as these seem to be larger in younger persons than in older individuals (Yogev-Seligmann et al., 2010). In the same way, sex differences with respect of task prioritization have been reported (Bayot et al., 2018), which complicates further this matter. The unclear effect of task prioritization in younger and older adults and in males and females may pose an extra challenge to the experimental situation when trying to compare outcomes from both groups and from both sexes. Because DTC in dual-task experiments are influenced by several factors, among them instruction of task priority, future experiments need to evaluate the effects of task instruction in specific groups of individuals, such as for example, younger vs older males or younger vs. older females.

Finally, it is necessary to acknowledge a limitation on the gait methodology. In most dual-tasks studies with gait, subjects are required to walk linearly on a gait device, while in our experimental situation subjects need to walk straight as well as negotiate the turns to follow the path in the walking area. Since the design of the present study intended to be as ecologically valid as possible, we decided to allow subjects to walk as in real life, that is continuously, and obtained global gait measurements from this design. Based on the results of the present study, we realized that such an environment poses different challenges to different populations and it is possible that a more traditional setting would show different results. Thus, future studies are encouraged to apply other dual-task settings to evaluate whether the present findings rely on the sole use of DL, independent of walking environment, or whether gait alterations due to DL are tightly related to the walking situation.

Conclusion

The current study has employed a novel approach to the dual-task paradigm using a DL task to investigate the interplay between, gait, sensorimotor abilities, and lateralized attentional constraints in healthy younger and older adults. The present data reveal that our dual-task paradigm induces asymmetric adjustments on gait in younger adults. However, these gait asymmetries differ from findings reported in our earlier study where older adults with different hearing status were assessed. In the present study, asymmetric gait changes in younger participants seem to arise as compensatory mechanisms rather than being detrimental for the execution of the dual-task. This finding is relevant to expand our knowledge about asymmetries in healthy populations. To date, gait asymmetries have not been widely studied in healthy adults (Morris et al., 2016), and certainly not in association with concrete cognitive demands in one sensorial modality like DL. Furthermore, the present study confirmed that older adults experience considerably higher step length variability than younger persons in a novel and complex dual-task situation. Future studies are encouraged to employ this paradigm on healthy populations on different life phases, such as middle-age persons or teenagers in order to expand our understanding of gait asymmetries and attentional control along the life span.

Acknowledgments

We thank Johan Jacob Espenes and Jesper Gundersborg Ansethmoen for helping with data acquisition.

Disclosure statement

No potential conflict of interest was reported by the author(s).

Funding

Financial support was received from the Faculty of Health Sciences, UIT- Arctic university of Norway (2016/5455), Norway and from the Norwegian Health Association (Nasjonalforeningen for folkehelsen) (2014/888)

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SUPPLEMENTARY TABLE I

Results for bilateral gait parameters

	CONDITION									
	Baseline		**Non-Forced**		**Forced-Right**		**Forced-Left**			
	Young	Old	Young	Old	Young	Old	Young	Old	RMANOVA, *p, (η²□)*	ANCOVA, *p, (η²□)*
	M (SD)	*M (SD)*	*M (SD)*	*M (SD)*	*M (SD)*	*M (SD)*	*M (SD)*	*M (SD)*	Cond./Interac./Group	Interac./Group/PTA
Mean										
Step length	60.8 (4.7)	68.2 (7.2)	57.9 (4.9)	64.1 (7.5)	57.3 (5.2)	63.1 (7.3)	57.2 (5.6)	63.1 (7.1)	**0.001(0.5)/0.001(0.5)/0.001(0.2)**	**0.001(0.5)/0.001(0.2)**/NS
Gait speed	0.9 (0.1)	1.2 (0.2)	0.9 (0.1)	1.1 (0.2)	0.8 (0.2)	1.1 (0.2)	0.8 (0.2)	1.1 (0.2)	**0.001(0.5)/** NS / NS	**0.001(0.5)** /NS /NS
Step width	16.8 (4.8)	8.0 (2.3)	16.5 (5.0)	8.3 (2.2)	16.6 (5.4)	8.1 (2.6)	17.1 (4.9)	8.7 (2.5)	NS / NS / **0.001 (0.6)**	NS/ **0.001 (0.5) /** NS
CoV (%)										
Step length	17.8 (3.2)	4.8 (2.1)	18.4 (5.6)	5.6 (2.9)	17.8 (3.1)	5.9 (5.6)	18.3 (2.8)	5.8 (2.7)	**NS** / NS / **0.001(0.8)**	NS **/** NS /**0.002 (0.8)**
Gait speed	26.3 (3.3)	4.3 (2.4)	27.6 (9.6)	5.9 (4.7)	26.5 (5.3)	6.6 (8.2)	26.2 (2.8)	6.9 (7.9)	NS / NS / **0.001(0.8)**	**NS/ NS / NS**
Step width	108.4 (18.8)	86.8 (36.9)	104.5 (23.5)	83.4 (34.7)	108.1(26.0)	89.9(38.4)	106.9 (21.3)	86.8 (36.9)	NS / NS / **0.001 (0.14)**	NS/ NS / NS

Note. RMANOVA and ANCOVA with Bonferroni correction for multiple comparisons. Units for Step length, Step width and Stride length = cm.; units for Gait speed = m/sec. Abbreviations:*M* = mean; *SD* = standard deviation; RMANOVA = repeated measures analysis of variance; ANCOVA = Analysis of covariance; CoV = Coefficient of Variation; Interac. = Interactions; PTA = Best Pure Tone Audiometry values; NS = Non Significant. CoV = Calculated with the formula: [mean/ SD] x 100%

SUPPLEMENTARY TABLE II Mean and standard deviations for gait parameters by foot expressed in mean values and coefficients of variation (CoV).

	CONDITIONS									
	Baseline		**Non-Forced**		**Forced-Right**		**Forced-Left**			
	Young	Old	Young	Old	Young	Old	Young	Old	RMANOVA, *p*, $(\eta^2_{\Box})$/	ANCOVA, *p*, $(\eta^2_{\Box})$
	M (SD)	*M (SD)*	*M (SD)*	*M (SD)*	*M (SD)*	*M (SD)*	*M (SD)*	*M (SD)*	Condition/Foot/Inter./Group	Foot/Inter./Group/PTA
Mean										
Step length R	61.1 (4.8)	62.9 (7.6)	57.8 (4.9)	62.5 (12.7)	57.0 (5.3)	62.9 (8.0)	57.2 (5.7)	62.9 (7.6)		
Step length L	60.6 (4.7)	63.2 (6.7)	58.0 (4.9)	64.1 (7.0)	57.5 (5.1)	63.3 (6.9)	57.1 (5.5)	63.3 (6.7)	NS / NS/ **0.001 (0.3)/0.001 (0.13)**	**NS** / NS / NS / **0.002 (0.16)**
Gait speed R	0.9 (0.1)	1.2 (0.2)	0.9 (0.2)	1.1 (0.2)	0.8 (0.2)	1.1 (0.2)	0.9 (0.2)	1.1 (0.2)		
Gait speed L	0.9 (0.1)	1.2 (0.2)	0.9 (0.2)	1.2 (0.2)	0.8 (0.2)	1.1 (0.2)	0.8 (0.2)	1.1 (0.2)	**0.001 (0.5)/** NS / NS / NS	**0.001(0.3)**/NS/ NS/ **NS**
Step width R	16.9 (5.1)	8.2 (3.3)	16.6 (6.0)	8.0 (4.2)	16.8 (5.3)	8.3 (2.9)	17.2 (5.2)	9.2 (2.6)		
Step width L	16.6 (5.2)	7.4 (2.4)	16.5 (5.4)	8.0 (2.4)	16.4 (5.7)	7.9 (2.4)	16.9 (4.9)	8.2 (2.6)	NS **/ 0.001 (0.3)**/ NS/ **0.007 (0.35)**	**NS** / NS/ NS/ **NS**
CoV (%)										
Step length R	17.2 (3.8)	4.7 (2.3)	18.5 (3.1)	4.8 (2.3)	18.4 (5.3)	5.4 (2.9)	18.3 (3.3)	5.4 (2.1)		
Step length L	18.3 (4.2)	4.2 (2.3)	18.2 (3.4)	5.6 (3.6)	16.9 (3.5)	5.7 (3.5)	18.1 (3.1)	5.5 (3.1)	NS/ NS/ **NS/ 0.001 (0.88)**	**0.001 (0.79)**/† **(0.16) /** NS/ NS
Gait speed R	26.1 (3.6)	4.4 (2.7)	26.3 (3.5)	6.0 (4.9)	25.9 (3.2)	6.4 (8.4)	25.8 (3.1)	7.1 (7.8)		
Gait speed L	26.6 (3.9)	4.2 (2.5)	28.2 (13.2)	6.0 (4.6)	26.8 (7.2)	6.6 (8.3)	26.4 (3.0)	6.7 (8.2)	NS/ NS / NS / **0.001 (0.87)**	**NS** / NS/ **0.001 (0.78)** / **NS**
Step width R	108.2 (19.0)	84.9 (37.6)	103.7(23.7)	78.4 (35.8)	106.9 (25.3)	86.9 (33.9)	107.1(21.4)	84.9 (37.6)		
Step width L	106.9 (21.1)	86.2 (35.1)	105.0 (23.6)	83.5 (37.8)	108.3 (26.4)	90.7 (41.4)	106.6 (22.3)	86.2 (35.1)	NS / NS / NS / **0.001 (0.16)**	NS / NS / NS / NS

Note: RMANOVA and ANCOVA with Bonferroni correction for multiple comparisons. Interactions marked with † refer to = Condition X Foot $p < 0.05$. Units for Step length, Step width and Stride length = cm.; units for Gait speed = m/sec. Abbreviations: *M* = mean; *SD* = standard deviation; RMANOVA = repeated measures analysis of variance; ANCOVA = Analysis of covariance; CoV = Coefficient of Variation; Interac. = Interactions; PTA = Best Pure Tone Audiometry values; NS = Non Significant. CoV = Calculated with the formula: [mean/ SD] x 100%.

Paper III

Gorecka, M.M., Vasylenko, O., Waterloo, K. & Rodríguez-Aranda, C. (2021). Assessing a sensory-motor-cognition triad in amnestic Mild Cognitive Impairment with dichotic listening while walking: A dual-task paradigm. *Frontiers in Aging Neuroscience*, *13*(757), Doi: 10.3389/fnagi.2021.718900

frontiers in Aging Neuroscience

ORIGINAL RESEARCH
published: 12 November 2021
doi: 10.3389/fnagi.2021.718900

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Assessing a Sensory-Motor-Cognition Triad in Amnestic Mild Cognitive Impairment With Dichotic Listening While Walking: A Dual-Task Paradigm

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A contemporary topic in aging research relates to the significance of cognitive changes proper to mild cognitive impairment (MCI) to higher risk of falls and gait deteriorations. The present study addresses this question in the amnestic type of MCI (aMCI) by examining a triad of interrelated comorbidities occurring in the MCI condition: attentional impairments, hearing loss and gait disturbances. To this end, we applied a dichotic listening (DL) test during over-ground walking. DL assesses spontaneous and lateralized auditory attention in three conditions (i.e., free report or Non-forced (NF), Forced-Right (FR) ear and Forced-Left (FL) ear). Earlier reports suggest that this dual-task paradigm evoke asymmetric gait effects on healthy controls, which are moderated by degree of hearing loss. Therefore, the aim of the present study was to evaluate the effects of DL on bilateral (data from both limbs) and lateralized (each limb separately) gait outcomes in a group of forty-three aMCI participants (mean = 71.19) and fifty-two healthy older controls (mean = 70.90) by using hearing loss as a covariate in all analyses. Results showed the aMCI group presented overall compromised gait parameters, especially higher gait variability in all DL conditions during lateralized attentional control. These findings were observed bilaterally, and no lateralized effects on gait were observed. Only after controlling for hearing acuity, gait asymmetries on step length variability emerged almost exclusively in healthy controls. It was concluded that hearing loss in the aMCI group together with higher attentional impairments preclude aMCI individuals to properly execute DL and therefore, they do not display gait asymmetries. The present data demonstrate that varied demands on attentional control dependent on hearing acuity affects gait negatively in healthy older adults and aMCI individuals in very different ways. The appearance of asymmetric effects seems to be a perturbation related to normal aging, while the lack of asymmetries but exaggerated gait variability characterizes aMCI. The present findings show the intricate interplay of sensory, cognitive, and motor deteriorations in different group of older adults, which stresses the need of addressing co-occurring comorbidities behind gait perturbations in individuals prone to develop a dementia state.

Keywords: dual-task, amnestic mild cognitive impairment (aMCI), hearing loss, gait, aging, dichotic listening

OPEN ACCESS

Edited by:
Francesco Panza, University of Bari Aldo Moro, Italy

Reviewed by:
Paulo Giusti Rossi, Federal University of São Carlos, Brazil
Riona Mc Ardle, Newcastle University, United Kingdom

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Received: *01 June 2021*
Accepted: *14 October 2021*
Published: *12 November 2021*

Citation:
Gorecka MM, Vasylenko O, Waterloo K and Rodríguez-Aranda C (2021) Assessing a Sensory-Motor-Cognition Triad in Amnestic Mild Cognitive Impairment With Dichotic Listening While Walking: A Dual-Task Paradigm. Front. Aging Neurosci. 13:718900. doi: 10.3389/fnagi.2021.718900

INTRODUCTION

Mild Cognitive Impairment (MCI) is the transitional stage between normal aging and dementia, which is characterized by objective impairment in one or more cognitive domains, preserved activities of daily living, and absence of dementia (Petersen et al., 2001; Winblad et al., 2004). In recent years, motor dysfunctions such as gait impairments have been associated with MCI (Verghese et al., 2008; Montero-Odasso et al., 2014; Bahureksa et al., 2017; König et al., 2017). For instance, during regular walking, individuals with MCI show slower gait velocity, shorter steps and stride length, and increased gait variability (Verghese et al., 2008; Montero-Odasso et al., 2012). These gait changes are associated with progression to dementia (Verghese et al., 2008; Doi et al., 2014; Beauchet et al., 2016; Bahureksa et al., 2017; Montero-Odasso et al., 2017; Goyal et al., 2019). For this reason, understanding the underlying causes of gait deteriorations in MCI is a central topic of investigation.

Various studies based on dual-tasks protocols have demonstrated that individuals with MCI show more deteriorated gait outcomes as compared to healthy controls, as well as worsen performance in the concomitant cognitive task (e.g., Martin et al., 2013). Thus, it is proposed that dual-task assessment may help in differentiating MCI subtypes (Montero-Odasso et al., 2014; Savica et al., 2017; Ghoraani et al., 2021). Since MCI is a heterogeneous condition with a broad range of preclinical impairments, it has been categorized into various subtypes such as amnestic, non-amnestic, single, and multi-domain types (Petersen et al., 2001). Nevertheless, at present research on MCI subtypes and gait impairments is rather scarce and inconsistent. For example, some studies addressing the matter have reported that individuals with amnestic MCI show slower gait and higher gait variability than non-amnestic MCI (Verghese et al., 2008; Doi et al., 2014); but the contrary has also been reported (Allali et al., 2016).

Because of all the MCI subtypes the most prone to progress into Alzheimer's disease is the amnestic type (aMCI) (Petersen, 2004; Winblad et al., 2004; Ward et al., 2013), investigation of gait alterations in aMCI needs to be pursued. However, in order to address the issue, implementation of a dual-task paradigm evaluating cognitive dysfunctions associated with aMCI such as memory and attentional/executive dysfunctions (Brandt et al., 2009; Johns et al., 2012) is required. Ideally, such a paradigm should resemble a daily action, that can be experimentally tested, and which evaluates various levels of cognitive loading. The need for stringent methods that are sufficiently ecologically valid for MCI individuals is central as MCI individuals show more difficulties on task prioritization (Lee and Park, 2018) and ecological relevance determines task priority (Doumas and Krampe, 2015).

Attempts to find appropriate cognitive tasks that enable the disclosure of gait alterations in aging populations have been conducted, such as the proposal by the Canadian Consortium on Neurodegeneration in Aging (CCNA, Montero-Odasso et al., 2019). This initiative suggests the use of specific tests in dual-tasking for optimization of the assessment of cognitive-motor interaction in aging populations. Most of the suggested tasks from the CCNA consortium are mental tracking tests, which have shown to be well-suited instruments challenging gait (Al-Yahya et al., 2011). In spite that robust data supports the use of these tasks in dual-task settings, there are serious limitations related to their ecological validity as well as their lack of specificity on the type of cognitive mechanisms measured (Gorecka et al., 2018). In addition, most of these tasks rely on varied sensorial modalities. For these reasons, our group has implemented a dichotic listening (DL) test, which has proven to be ecologically valid for older adults (Gorecka et al., 2018). Indeed, DL has advantageous features for its implementation on dual-task paradigms. To begin with, DL is a robust neuropsychological procedure assessing divided and sustained attention (Kimura, 1967), as well as various aspects of executive control (Hugdahl et al., 2009) in the auditory modality. Additionally, the neural mechanisms underlying DL have been largely explored (Ocklenburg et al., 2014). In DL, different auditory stimuli are presented simultaneously to both ears, and subjects are asked to ignore or report the most salient sound or focus on a single ear. Right-handed individuals display a right-ear advantage (REA) due to the decussation of dominant language-processing in the brain (see Bryden, 1988). To date, few studies have assessed DL on individuals with MCI. The limited findings have shown that individuals with MCI fail to allocate attention to the left -side and simultaneously ignore right-side information due to a failure to sustain attention and inhibit stimuli (Andersson et al., 2008; Takio et al., 2009; Bouma and Gootjes, 2011; Utoomprurkporn et al., 2020). The same difficulty also exists to a lesser extent in cognitively healthy older adults, which indicates that focusing attention to the left-side poses the heaviest load in allocation of cognitive resources among older people (Andersson et al., 2008; Takio et al., 2009; Bouma and Gootjes, 2011; Kompus et al., 2012; Passow et al., 2012; Westerhausen et al., 2015). Interestingly, most investigations using DL in MCI populations have been conducted for the evaluation of auditory function connected to the development of dementia (Idrizbegovic et al., 2011; Häggström et al., 2018; Swords et al., 2018). This piece of information linking auditory function, DL and dementia development in MCI is noteworthy for the present study.

In our laboratory, we have applied a DL paradigm with different attentional conditions during over-ground walking in healthy older adults. Our first study (Gorecka et al., 2018), showed important asymmetrical effects on spatiotemporal measures of gait that were modulated by degree of hearing loss in cognitively normal older participants. Because the incidence of central auditory dysfunction is higher in elders with MCI (Idrizbegovic et al., 2011), the application of DL during walking will allow for the evaluation of factors known to interact with gait and which are particularly affected by the MCI condition. Taken the above facts together, the present study aims to apply the same dual-task paradigm as in our previous investigations to individuals with amnestic MCI. The main goal is to determine whether an aMCI group show quantitative or qualitative impairments on gait as compared to healthy age-matched controls. According to Simoni et al. (2021) quantitative impairments in gait are related to perturbations on typical spatio-temporal parameters such as gait speed, step length or step width, while qualitative impairments concern alterations on gait harmony, that is on symmetric outcomes of gait. Relying on the literature about MCI development and gait (e.g., Montero-Odasso et al., 2014), quantitative changes are expected to arise in the aMCI group in terms of more exaggerated deteriorations across all spatiotemporal parameters. However, we also expect to obtain qualitative dysfunctions unique to the aMCI group, such as clear asymmetric gait outcomes in those conditions with high attentional load, which according to our own data (Gorecka et al., 2018; Castro-Chavira et al., 2021) would arise during the DL conditions where spontaneous attention and attention to left side are required. Since our previous studies showed a modulating effect of hearing status on gait and DL, we also expect that higher hearing difficulties in aMCI participants will moderate the effects on gait induced by the dual-task procedure.

MATERIALS AND METHODS

Participants and Evaluations

MCI Group

Sixty individuals diagnosed with MCI by a senior geriatrician or neurologist at the Department of Geriatrics and the Department of Neurology at the University Hospital of North Norway (UNN), Tromsø were recruited for the study. These individuals were referred to the specialists initially for the assessment of memory problems and they were diagnosed with F06.7 Mild cognitive disorder in accordance with the International Statistical Classification of Diseases and Related Health Problems (ICD-10) criteria. All these individuals underwent detailed examinations at the hospital that included standard laboratory and cognitive tests as well as brain imaging assessments. Inclusion criteria for this group was a referral from the specialists with a MCI diagnosis, being right-handed, Norwegian native speaker, not depressed and able to move and walk freely.

Older Adults in the Control Group

Fifty-eight, age-matched older adults volunteered as control participants through advertisements at the local senior citizens' center, flyers, and as well as by means of word of mouth. Inclusion criteria for this group were being right-handed and native Norwegian speakers; free from any musculoskeletal, neurological or walking difficulties and no symptoms of clinical depression or cognitive impairment. To rule out any of the above criteria, all participants completed a semi-structured interview to collect information about their health status and health history, education and daily functioning. Furthermore, all participants were screened for depression using the Beck Depression Inventory II (BDI-II; Beck et al., 1996) and for global cognitive status with the Mini-Mental State Examination (Folstein et al., 1975)—Norwegian version (MMSE-NR; Strobel and Engedal, 2008). Only participants with a of MMSE cut-off score > 27 and not depressed according to the adapted criteria on BDI for older adults (Rodríguez-Aranda, 2003) were recruited for the study.

General Initial Evaluation for Both MCI and Older Volunteers

Although the MCI participants were screened for depression and global cognitive status at the University Hospital, we tested them for these aspects after enrollment in the study to standardize dataset of this investigation. Thus, all participants, both MCI individuals and older controls were evaluated with the MMSE-NR (Strobel and Engedal, 2008), the Beck Depression Inventory II (BDI-II; Beck et al., 1996), and the Falls Efficacy Scale International (FES-I; Yardley et al., 2005) to check for fear of falling. In addition, the Norwegian version of the F-36 questionnaire (Loge et al., 1998) was also applied to check the participants' subjective evaluation of their health status and the Handedness Inventory (Briggs and Nebes, 1975) to confirm hand preference.

As part of a major umbrella project at the Department of Psychology, UIT—The Arctic University of Norway, Tromsø, about motor functions and cognition in aging, this study was approved by the Regional Committee for Medical and Health Research Ethics—REK (2009/1427). Written and informed consent was acquired from all participants prior to the study.

Procedures and Assessments

Even though, the main goal of this investigation is to assess a dual-task paradigm with dichotic listening (DL) while walking, there are various prerequisites necessary to perform before the dual-task paradigm could be carried out. All the participants needed to be tested with a neuropsychological battery to define and assure their group affiliation (amnestic MCI, vs. controls). Also, they needed to undergo audiometric screening to settle their hearing status and assure their hearing was well enough to perform the DL task. Thereafter, the dual-task paradigm could be performed. A clear description of this paradigm involves the methods for acquisition of gait parameters, DL-testing, and conduction of the dual-task paradigm. Based on the above, in the following section we will first present the methods related to the prerequisites (neuropsychological and audiometric assessments). Next, we will present the methods related to the dual-task paradigm (i.e., recording of gait parameters, DL test, and dual-tasking). Finally, a description of the overall data acquisition will be given.

Neuropsychological Assessment and Group Assignment

Since the present investigation aims to evaluate amnestic MCI participants against cognitively healthy age-matched controls, a thorough neuropsychological assessment was conducted. This allowed us to assign participants referred from the hospital to a particular MCI subgroup (i.e., amnestic, non-amnestic, multiple domain) and to corroborate that older volunteers conforming the control group were indeed free of cognitive impairments. To this end, we employed eleven neuropsychological tests to assess three cognitive domains:

Executive Function/ Working Memory/Attention Domain. For assessment of this domain, we relied on four tests. The subtest Digit Span backward from Wechsler Adults Intelligence Scale 4th Edition (WAIS-IV, Wechsler, 2008) which examines attention and working memory was used. Also, the interference part word/color of the Stroop Word Color Test (Golden, 1978) and the Trail Making Test B (TMT B; Reitan and Wolfson, 1993) were used to examine executive functions, like inhibition and cognitive flexibility. Finally, the phonemic fluency test (COWAT, Benton, 1969) was applied to assess inhibition, ability to initiate systematic lexical search and working memory.

Memory Domain. Logical Memory I and II from Wechsler Memory Scale 3rd edition (Wechsler, 1997); the subtest Digit Span forward from Wechsler Adults Intelligence Scale 4th Edition (WAIS-IV, Wechsler, 2008), as well as semantic fluency (Newcombe, 1969) were used to measure memory abilities.

Visuospatial Abilities Domain. Visuospatial processing was examined by applying Block Design from WAIS-IV (Wechsler, 2008), the Clock Drawing Test (CDT, Shulman, 2000) and Trail Making Test A (TMT A; Reitan and Wolfson, 1993). The first two are tests commonly used to evaluate visual memory and construction ability, while the TMT A is employed in the assessment of visuospatial ability, motor skills in addition to processing speed.

Procedures for Group Assignment. Mild cognitive impairment participants in this study were classified according to neuropsychological criteria of MCI suggested by Jak et al. (2009) and Bondi et al. (2014). These criteria propose that in order to qualify as MCI in a particular domain, it is required that an individual shows impaired performance greater than one standard deviation (SD) below appropriate age-norms. Thus, participants in the MCI group were classified as amnestic MCI if they were impaired on tests belonging to the memory domain. As part of a major aging project at our institution, we also classified the referred patients into the MCI categories of non-amnestic (if they presented impairment in a non-memory domain) and of multiple domain (if they presented impairment in various cognitive domains). As for the older volunteers, they were confirmed as cognitively normal, if their performance on each of the assessed domains was within 1 SD of the normative expectations.

Audiometric Screening

All participants completed audiometric screening in a double-walled, sound- attenuated room using pure-tone audiometry (Madsen Itera II, GN Otometrics, Denmark). Hearing sensitivity was measured calculating the Pure Tone Average (PTA) from hearing thresholds of the frequencies 500, 1,000, 2,000, and 4,000 Hz. The results of the PTA showing thresholds > 45 dB scores as well as an interaural difference larger than 15 dB were criteria for exclusion of participants (Saliba et al., 2009).

Acquisition of Gait Parameters

Spatiotemporal parameters of gait were acquired using the OptoGait System (OptoGait, Microgate, Bolzano, Italy). The system consists of transmitting-receiving bars aligned in parallel and creating a 7 × 1.3 m area that quantifies spatiotemporal gait parameters by using photoelectric cells that register interference in light signals. The sensors in the OptoGait system are placed over ground in a rectangular fashion where subjects walk within in circles. Ninety-six LED diodes are positioned on each bar one centimeter apart at three millimeters above the ground. When subjects pass between two bars positioned in parallel with the ground, transmission and reception are blocked by their feet, automatically calculating spatio-temporal parameters. Data were extracted at 1,000 Hz and saved on a PC using OptoGait Version 1.6.4.0 software. Gait parameters examined were gait speed, step length, and step width, for both feet and per foot. Linear measures including the mean (M) and the coefficient of variation [CoV, based on the formula (SD/mean) × 100%] were calculated for each gait parameter. All walking conditions were recorded with two Logitech web cameras from different angles to overlook any difficulties or changes during walking conditions. The Optogait system has proven to be a highly reliable and valid instrument (Lee et al., 2014).

Dichotic Listening Task

As the concomitant cognitive task to walking, we applied the Bergen Dichotic Listening Test (Hugdahl and Andersson, 1986). The test consists on the simultaneous and randomized presentation of six syllables: /ba/ /ta/ /pa/ /ga/ /da/ /ka/. Each pair of syllables has a duration of 350 ms. The syllables were paired with each other in all possible combinations to form 36 different syllable pairs. From these, the homonymic pairs (e.g., ba–ba) were included in the test as perceptual control, but not considered in statistical analysis. The syllables were read by a Norwegian-speaking male voice with constant intonation and intensity with a time interval of 4,000 ms. The total duration of each DL condition was 3 min. The DL procedure has three conditions: The Non-forced condition (NF) was always conducted first where participants were instructed to report the syllable they heard the clearest. The NF condition evaluates spontaneous attentional abilities as subjects choose freely which stimulus they report. Thereafter, two conditions followed where participants were instructed to pay attention either to the right ear (Forced-Right condition, FR) or to left ear (Forced-Left condition, FL) while ignoring stimuli from the opposite ear. The forced attention conditions evaluate volitional lateralized attentional control to the respective side. On each DL-condition, the following scores are calculated: Number of correct responses and homonyms, number of errors/no responses and calculation of a laterality index (LI = $\left[\frac{(RE - LE)}{RE + LE}\right] \times 100$) for each condition. These scores were used in the statistical analyses for DL. The FR and FL were counterbalanced across subjects depending on their ID number. Participants with ID numbers that were odd numbers received FR before FL. The syllables were presented using wireless noise-canceling headphones.

Dual-Task Paradigm

In this part of the study, all participants were evaluated for single walking as well as while performing the three DL conditions (i.e., Non-forced, NF; Forced-Right, FR; Forced-Left, FL) during walking. Thus, four conditions confirmed the paradigm: (1) A baseline walking condition (i.e., only walking); (2) NF while walking; (3) FR while walking; and (4) FL while walking. It is important to remark that no previous training or habituation sessions were conducted as we aimed to obtain data from naïve subjects exposed to a single experience. The experiment was

FIGURE 1 | Illustration of the dual-task experimental setting and a volunteer performing the paradigm.

conducted in a rectangular shaped room. An illustration of the experimental setting is shown on **Figure 1**.

Baseline Condition (Only Walking)

Prior to the experiment, participants were given a demonstration trial of the walking direction by the experimenter within the gait analysis system, and they were required to confirm the well understanding of these instructions. To allow for the best ecological valid situation, participants were asked to walk in a self-selected, comfortable walking speed (usual), counterclockwise. The decision of the counterclockwise direction agrees with the natural tendency of right-handed individuals to turn to the left (e.g., Mohr et al., 2003; Lenoir et al., 2006). The Optogait system started recording the gait measures when the subject took their first footstep, initiated by a verbal signal. In the baseline condition, participants were instructed to walk for 1 min within the Optogait field to collect baseline measurements without performing the cognitive task. Based on pilot trials, the baseline condition was shorter (1 min) than the rest of the dual-task conditions (3 min). The reason was to obtain a balanced situation in which subjects did not get tired or lightheaded while allowing acquisition of enough gait data.

Preparations for Dual-Tasking

Participants were given a demonstration trial of how to perform the DL before the dual-task was conducted. First, the experimenter explained to the subjects that they will wear headphones while walking again at their usual pace, and that they will be exposed to different syllables on each ear. Participants were also asked to wear around the neck a small portable digital recorder to record their responses during the trial. A sheet of paper with the six printed syllables used in DL test was shown to the participants to clarify the sort of stimuli used. A similar sheet of paper was attached on one wall at the end of the walkway to remind participants which stimulation they should expect. Then, they were required to listen and respond loudly to three stimuli presentations from the DL test while wearing headphones in a stand still position. In this way, we ensured good comprehension of the instructions. Volume of the auditory stimuli was also adjusted for each person prior to the testing. Moreover, we emphasize equal task prioritization by asking subjects to keep walking and execute the DL task as accurate as possible during the entire trial.

DL Instructions

DL Non-forced condition: In this condition participants were asked to report loudly the syllables best perceived. Instructions were: "We ask you to loudly say the clearest syllable you detect each time you get stimulation. Please walk at your usual pace all the time while responding. We remind you that only six possible syllables (those shown on the paper) will be presented and we ask you to perform as well as possible walking continuously in rounds in the designated area as previously demonstrated, while reporting the clearest sounds you perceive." *DL Forced-Right condition:* In this condition, same instructions were given with the only difference that we required subjects to report loudly only the syllables presented to the *right ear*. *DL Forced-Left condition:* Again, same instructions yielded, but this time participants were asked to report syllables presented to the *left ear*.

Conduction of DL While Walking

In all dual-task conditions, the dichotic listening task was initiated simultaneously as the subject lifted a foot to initiate walking, again when the experimenter gave a verbal cue. At the time of testing, DL-responses were recorded in the digital voice recorder and also written down by the experimenter on a sheet of paper. Data acquisition for gait parameters were conducted in the 1-min trial for baseline and on each 3-min trial of the DL conditions during walking. When necessary, short breaks were given between baseline and on each of the dual-task conditions. After the experiment was completed, two additional experimenters listened the recorded DL answers from the digital recorder and checked them against the written answers to ensure the reliability of the data. Thereafter, the experimenters manually inserted all DL answers in the E-prime 2.0 Software (Psychology Software Tools, Inc., Pittsburgh, PA, United States) for the calculation of DL scores.

General Procedure for All Data Acquisition

The study took place at the Department of Psychology, UiT Arctic University of Norway. The duration of the whole procedure was about 3 h and testing sessions were divided into two sessions to avoid fatigue. In the first session, participants were interviewed to acquire their demographic background and health history in a sound-attenuated room. Also, in this session and under the same environment, they underwent audiometric screening, and they were evaluated with the neuropsychological test battery. In the second session, participants answered to remaining questionnaires and they performed the dual-task paradigm.

Statistical Analyses

All analyses were performed with the statistical package IBM SPSS Statistics 26. Group comparisons for demographics, background variables, cognitive tests and questionnaires were performed with independent *t*-tests.

Classification of MCI Subgroups

We applied the method used by Aarsland et al. (2009), where raw cognitive scores were converted into z-scores using the mean and standard deviations of an existing database of cognitively healthy older adults (n = 103) from North Norway collected at our laboratory. Thereafter, an averaged composite score by domain was calculated for each participant. Adjustments regarding age, sex and education were performed *via* multiple regression analyses relying on the cognitively healthy older adults' database for each cognitive domain. The intercepts and beta weights from these calculations were used to obtain predicted z-scores for each participant in the study.

Dichotic Listening Data

A series of factorial analyses of variance with repeated measures in one factor were carried out. For DL data, the design 2 Group (aMCI, Control) × 2 Ear (right, left) × 3 Condition (NF, FR, and FL) was used. In case of a significant omnibus test, univariate tests were performed. Multivariate tests for simple main effects were employed in the case of significant interactions.

Gait Parameters

For gait, we also applied a series of factorial analyses of variance with repeated measures in one factor. This time, we analyzed the mean and coefficient of variations (CoV) separately for each gait parameter. First, we analyzed bilateral outcomes (i.e., data from both limbs together) and then lateralized outcomes (i.e., separate data for each limb). In the first set of analyses, mixed-ANOVAs were conducted for bilateral gait parameters with the design 4 Condition (Baseline, NF, FR, and FL) × 2 Group (aMCI, Control). Next, we investigated the existence of possible asymmetric effects on gait parameters due to the DL condition with the mixed-ANOVA design of 4 Condition × 2 Group × 2 Feet. In case of a significant omnibus test, univariate tests were performed. Multivariate tests for simple main effects were employed in the case of significant interactions.

Effects of Hearing Loss on DL and Gait

Since age-related hearing impairment has shown to modulate effects of lateralized attention on gait parameters in previous studies from our laboratory (Gorecka et al., 2018), we performed different ANCOVAs by using Best PTA as covariate. In this investigation, the moderating effects of hearing status were explored on both gait and on DL data. The use of Best PTA was chosen as it depicts the lowest functional threshold, which enables hearing compensation (Linssen et al., 2014).

In all analyses, Greenhouse–Geisser corrections were chosen when the sphericity assumption was not met. Significant interactions or main effects involving group differences were followed up with appropriate *post hoc* analyses. The Bonferroni correction was applied across all factorial analyses.

RESULTS

Group Assignment

By applying a cut-off of ≥ 1 SD lower than the expected z-score on the memory domain we were able to identify 43 amnestic MCI individuals from the original pool of 60 referred participants. As for the control group, we were able to confirm that 52 out of 58 older adults recruited originally as control volunteers were cognitively healthy and thus, these participants were retained for the present study.

Demographics

Results from demographic variables are shown in **Table 1**. No significant differences were found between the groups regarding age or education. Positive measures from the Handedness Inventory confirmed participants were right-handed. However, significant group differences were found where the aMCI group reported significantly more preference to the use of right hand than healthy controls. No group differences were found in terms of self-reported health status, fear of falling or depression.

Audiometric Scores

Table 1 also shows pure tone average scores interaurally for both groups. The aMCI group had significantly higher hearing thresholds compared to healthy controls on all outcomes.

Neuropsychological Results

Results from the neuropsychological assessments are displayed in **Table 2**. The control group showed significantly better performances than aMCI individuals on all neuropsychological measures.

TABLE 1 | Demographic characteristics and initial assessments by group.

	Controls (n = 52)	aMCI (n = 43)	
Gender (men/women)	**24/28**	**20/23**	
	M (SD)	**M (SD)**	***t***
Age	70.90 (7.35)	71.19 (8.75)	0.17
Education (years)	13.18 (3.55)	11.90 (3.91)	−0.65
MMSE-NR	29.27 (1.07)	25.67 (3.28)	−7.45***
BDI-II	5.39 (5.46)	6.08 (4.77)	0.21
Handedness	19.88 (4.47)	22.02 (3.37)	2.56*
FES–I	19.26 (4.02)	19.66 (4.67)	0.41
SF-36	111.98 (45.52)	105.00 (9.62)	0.31
PTA right (dB)	23.74 (11.21)	32.69 (16.17)	3.17**
PTA left (dB)	25.56 (11.83)	32.09 (13.88)	2.47*
PTA Worst (dB)	27.45 (12.53)	35.41 (16.90)	2.68**
PTA Best (dB)	21.53 (9.62)	29.37 (12.90)	3.39***

*M, mean; SD, standard deviation; MMSE-NR, mini mental status examination - norwegian revision; BDI-II, Becks Depression Inventory; FES-I, Falls Efficacy Scale International; SF-36, Short Form Survey 36 items; PTA, Pure Tone Average; dB, decibel. *p ≤ 0.05; **p ≤ 0.01; and ***p ≤ 0.001.*

TABLE 2 | Means and standard deviations from neuropsychological tests by cognitive domain.

	Controls(n = 52)		aMCI(n = 43)		
Domain	**M**	**(SD)**	**M**	**(SD)**	***t***
Executive functions/working memory					
TMT B, sec	92.10	(27.56)	195.67	(157.53)	5.04***
Stroop WCI	32.52	(8.87)	27.63	(11.61)	−2.24*
DigitSpan B	8.08	(1.49)	6.37	(1.59)	−5.32***
COWAT	13.83	(3.21)	11.16	(4.17)	−3.13**
Memory					
Log Memory I	23.93	(6.04)	8.16	(6.13)	−10.14***
Log Memory II	27.56	(6.09)	7.39	(8.17)	−11.74***
DigitSpan F	8.90	(1.76)	7.37	(1.28)	−4.69***
Sematic Fluency	16.54	(3.52)	12.78	(4.27)	−4.13***
Visuospatial					
CDT	6.93	(0.23)	6.10	(1.71)	−3.49**
TMT A, sec	36.07	(15.09)	56.64	(24.81)	5.31***
Block Design	38.23	(8.02)	27.61	(9.76)	−5.76***

*M, Mean; SD, standard deviation; aMCI, amnestic Mild Cognitive Impairment; CDT, Clock Drawing Test; TMT, Trail Making Test; Sec, seconds; Stroop WCI, Stroop Word-Color Interference; COWAT, Controlled Oral Word Association Test; DigitSpan B, Digit span backward; DigitSpan F, Digit span forward; Log Memory, Logical Memory. *p < 0.05; **p < 0.01; and ***p < 0.001.*

Dichotic Listening Results

Correct Responses

Three-way MANOVA showed only significant main effect for Ear [Pillai's Trace = 0.33, F (1, 93) = 46.66, $p < 0.001$, $\eta^2_p = 0.33$]. No main effect of group [F (1, 93) = 0.040, p = NS] or condition were found, [Pillai's Trace = 0.01, F (2, 92) = 0.045, p = NS] However, there was a significant interaction for Condition × Ear [Pillai's Trace = 0.16, $p < 0.001$, F (2, 92) = 9.98, $p < 0.001$, $\eta^2_p = 0.16$]. These results are as expected and naturally due to the change in focus of attention driven by the instructions. Additionally, an interaction effect between Condition × Ear × Group [Pillai's Trace = 0.07, F (2, 92) = 3.68, $p < 0.05$, $\eta^2_p = 0.07$] was observed. Simple main effects analyses of this interaction revealed that healthy controls produced significantly less correct right-ear responses in the FL conditions, as compared to right-ear responses in the NF, $p < 0.01$, and the FR conditions, $p < 0.001$ (see **Figure 2**). Furthermore, the cognitively healthy controls also reported significantly less from the left-ear in NF ($p < 0.01$) and FR ($p < 0.001$) compared to the FL condition. Concerning the aMCI group, these subjects reported significantly more correct left-ear responses in NF than in FR. No further significant differences were seen (see **Figure 3**). Controlling for effects of hearing on correct responses: After controlling for hearing, a significant interaction between Condition × Ear, [Pillai's Trace = 0.08, F (2, 91) = 3.85, $p < 0.05$, $\eta^2_p = 0.08$] was still present and showed same results as previously. The interaction effect was seen in healthy controls, [Pillai's Trace = 0.13, F (2, 49) = 3.57, $p < 0.05$, $\eta^2_p = 0.13$], but not in aMCI. However, the original significant interaction effect between Condition × Ear × Group was no longer significant [Pillai's Trace = 0.05, F (2, 91) = 2.49, p = NS].

Laterality Index

Further analysis for laterality index (LI), showed a main effect of Condition, [Pillais's Trace = 0.11, F (2, 92) = 5.51 $p < 0.006$, $\eta^2_p = 0.11$] and an interaction effect Condition × Group [Pillai's Trace = 0.07, F (2, 92) = 3.27, $p < 0.05$, $\eta^2_p = 0.16$]. This interaction effect showed that the cognitively healthy control group had significantly higher REA, i.e., laterality index in the NF, 22.7% (SD = 23.43), and FR, 26.7%, (SD = 29.72) condition compared to FL, 8.4% (SD = 32.67). There were no significant differences in laterality index between the conditions in the aMCI group, with 17.7% (SD = 32.23) in the NF condition, and 24.9% (SD = 37.2) and 19.5% (SD = 36.0) in FR and FL respectively. Controlling for effects of hearing on LI: The significant interaction on LI was no longer significant when controlling for Best PTA [Pillai's Trace = 0.04, F (2, 91) = 1.95, p = NS].

DL Errors and Non-responses

We distinguished the errors into real errors (commissions) and non-responses (omissions). For the errors, there was only a main effect of Condition [Pillai's Trace = 0.15, F (2, 91) = 8.25, $p < 0.001$, $\eta^2_p = 0.15$]. *Controlling for effects of hearing on errors/non-responses:* By controlling for hearing acuity, this effect was no longer significant. For non-responses, we also found a significant main effect of Condition [Pillai's Trace = 0.20, F (2, 92) = 11.67, $p < 0.001$, $\eta^2_p = 0.20$] that persisted after controlling for Best PTA [Pillai's trace = 0.10, F (2, 91) = 5. 03, $p < 0.01$, $\eta^2_p = 0.10$].

Results for Gait Outcomes

Bilateral Results (i.e., Right and Left-Foot Data Together)

The analyses performed with series of two-way MANOVAs on the mean and CoV values of step length [mean: Pillai's Trace = 0.58, F (3, 91) = 42.72, $p < 0.001$, $\eta^2_p = 0.58$; CoV: Pillai's Trace = 0.15, F (3, 91) = 5.62, $p < 0.001$, $\eta^2_p = 0.16$],

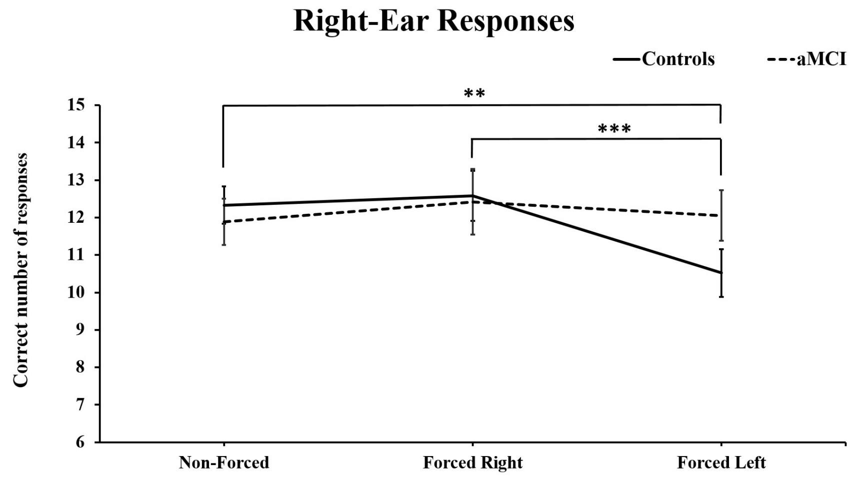

FIGURE 2 | Mean and ± SEM for correct right-ear responses across three dichotic listening conditions. aMCI, amnestic Mild Cognitive Impairment. (**$p < 0.01$; and ***$p < 0.001$) Reported significant differences are only for the control group.

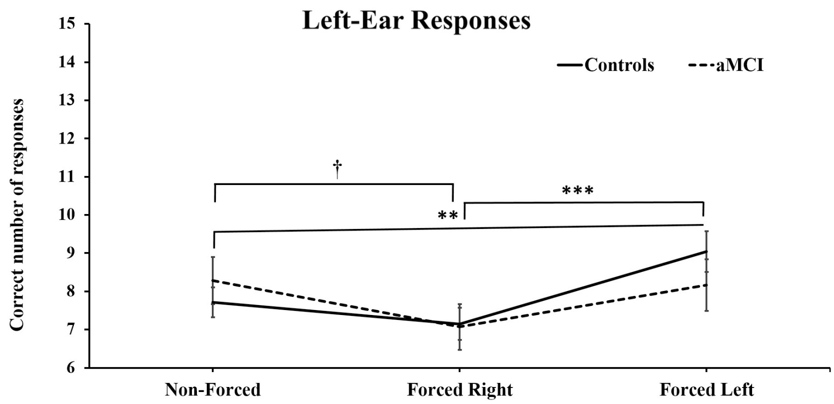

FIGURE 3 | Mean and ± SEM for correct left-ear responses across three dichotic listening conditions. aMCI, amnestic Mild Cognitive Impairment. The reported † denotes significant differences of $p < 0.05$ for aMCI group and the ** and *** denotes significant differences of $p < 0.01$ and $p < 0.001$*)* respectively, for healthy controls.

and gait speed [mean: Pillai's Trace = 0.57, F (3, 9) = 40.68, $p < 0.001$, $\eta^2_p = 0.57$; CoV: Pillai's Trace = 0.10, F (3, 91) = 3.69, $p < 0.05$, $\eta^2_p = 0.11$] showed a main effect of condition in which shorter steps, slower speed and increased variability were found during the dual-task conditions as compared to baseline. In contrast, no main effect of condition was found for the mean [Pillai's Trace = 0.06, F (3, 91) = 2.08, p = NS] or CoV [Pillai's Trace = 0.06, F (3, 91) = 1.9, p = NS] of step width. No significant interactions were found.

Furthermore, a main effect of group was found in these three spatio-temporal parameters for mean values [step length: F (1, 93) = 21.44, $p < 0.001$, $\eta^2_p = 0.19$; gait speed: F (1, 93) = 40.68, $p < 0.001$, $\eta^2_p = 0.20$; step width: F (1, 93) = 26.63, $p < 0.001$, $\eta^2_p = 0.22$] showing more deteriorated results in the aMCI group as compared to healthy controls. Likewise, an effect of group was found for CoVs for step length [F (1, 93) = 26.58, $p < 0.001$, $\eta^2_p = 0.22$] and gait speed [F (1, 93) = 22.11, $p < 0.001$, $\eta^2_p = 0.19$] where aMCI demonstrated higher variability than controls. No main effect of group was observed for CoV in step width [F (1, 93) = 0.14, p = NS] and no significant interactions were found. *Controlling for effects of hearing on bilateral gait data:* By controlling for hearing status none of the results mentioned above were modified, except for CoV of gait speed, where the main effect of condition was no longer present [Pillai's Trace = 0.03, F (3, 90) = 0.92, p = NS]. Results from the bilateral analyses are presented in **Supplementary Table 1**.

Lateralized Results (i.e., Right Foot and Left Foot Separately)

A series of three-way MANOVAS were performed in this part of the analyses where the factors of condition (x 4), group (x 2) and foot (x 2) were tested. By conducting these lateralized analyses, we assessed possible asymmetric effects of DL on each of the gait measures. Results did not show any significant main effect of foot for neither gait speed [mean: Pillai's Trace = 0.01, F (1, 93) = 1.29, p = NS; CoV: Pillai's Trace = 0.01, F (1, 93) = 0.73, p = NS] or step

TABLE 3 | Mean and standard deviations for gait parameters by foot expressed in mean values and coefficients of variation (CoV).

	Conditions									
	Baseline		Non-forced		Forced-right		Forced-left			
	Controls M (SD)	aMCI M (SD)	Controls M (SD)	aMCI M (SD)	Controls M (SD)	aMCI M (SD)	Controls M (SD)	aMCI M (SD)	RMANOVA, *p*, (η^2_p) Condition/Foot/Interact./Group	ANCOVA, *p*, (η^2_p) Foot/Interact./Group/PTA
Mean										
Step length R	62.8 (12.4)	55.4 (8.8)	60.4 (10.1)	51.6 (9.4)	58.7 (10.0)	50.4 (8.3)	58.9 (9.9)	50.5 (8.9)		
Step length L	63.9 (9.0)	55.5 (8.9)	60.7 (9.2)	51.9 (9.2)	59.2 (9.4)	50.3 (9.4)	59.2 (9.4)	50.3 (9.4)	0.001 (0.3)/ NS/ NS//0.001 (0.2)	NS/0.026 (0.1)/0.003 (0.1)/0.003 (0.9)
Gait speed R	1.1 (0.2)	0.8 (0.2)	1.0 (0.2)	0.7 (0.2)	0.9 (0.2)	0.7 (0.2)	1.0 (0.3)	0.7 (0.2)		
Gait speed L	1.1 (0.2)	0.9 (0.2)	1.0 (0.2)	0.7 (0.2)	0.9 (0.3)	0.7 (0.2)	1.0 (0.3)	0.7 (0.2)	0.001 (0.4)/ NS /NS /0.001 (0.2)	0.03 (0.5)/NS/0.001 (0.1)/0.001 (0.3)
Step width R	9.3 (3.6)	13.5 (3.7)	9.7 (2.7)	13.2 (3.3)	10.3 (4.2)	13.1 (3.5)	9.0 (4.0)	13.2 (3.8)		
Step width L	9.0 (3.8)	12.8 (3.1)	9.3 (3.2)	13.1 (3.5)	9.7 (4.2)	13.1 (4.0)	10.6 (3.5)	13.5 (3.7)	NS / 0.002 (0.1)/ NS/ 0.001 (0.2)	NS / NS/0.001 (0.1)/0.001 (0.1)
CoV (%)										
Step length R	8.6 (6.2)	15.4 (7.5)	6.9 (5.7)	13.9 (7.3)	7.9 (6.5)	16.6 (9.9)	9.4 (7.9)	15.5 (7.9)		
Step length L	8.6 (7.0)	15.4 (7.1)	7.7 (7.0)	13.5 (7.4)	7.9 (5.8)	17.0 (10.0)	9.4 (7.7)	15.1 (7.5)	0.001 (0.07)/0.015 (0.04)/NS/0.001 (0.2)	0.009 (0.04)/0.001 (0.2)/0.001 (0.1)
Gait speed R	8.7 (9.8)	20.9 (11.8)	9.2 (9.0)	21.6 (10.6)	12.4 (16.1)	26.5 (35.7)	11.9 (15.1)	27.2 (42.9)		
Gait speed L	8.4 (9.1)	20.6 (11.6)	9.4 (8.6)	21.3 (10.6)	12.9 (15.2)	22.5 (35.8)	11.9 (14.7)	22.2 (11.6)	0.029 (0.03)/ NS/ NS/0.001 (0.06)	NS/NS/ 0.001 (0.13)/0.011 (0.07)
Step width R	83.2 (43.6)	90.6 (31.9)	77.1 (29.4)	85.8 (33.9)	85.5 (29.9)	85.8 (29.8)	85.7 (35.4)	86.6 (32.7)		
Step width L	81.3 (31.4)	90.6 (37.1)	82.9 (35.5)	83.0 (26.5)	87.6 (31.8)	85.5 (29.8)	86.6 (32.7)	83.6 (28.3)	NS / NS / NS / NS	NS / NS / NS/ NS

RMANOVA and ANCOVA with Bonferroni correction for multiple comparisons. Interactions marked with †refer to = Condition × Foot $p < 0.05$. Units for Step length, Step width and Stride length = cm.; units for Gait speed = m/s. M, mean; SD, standard deviation; R, Right; L, Left; RMANOVA, repeated measures analysis of variance; ANCOVA, Analysis of covariance; CoV, Coefficient of Variation; Interact., Interactions; PTA, Best Pure Tone Audiometry values; NS, non-significant; CoV, calculated with the formula: (SD/mean) × 100.

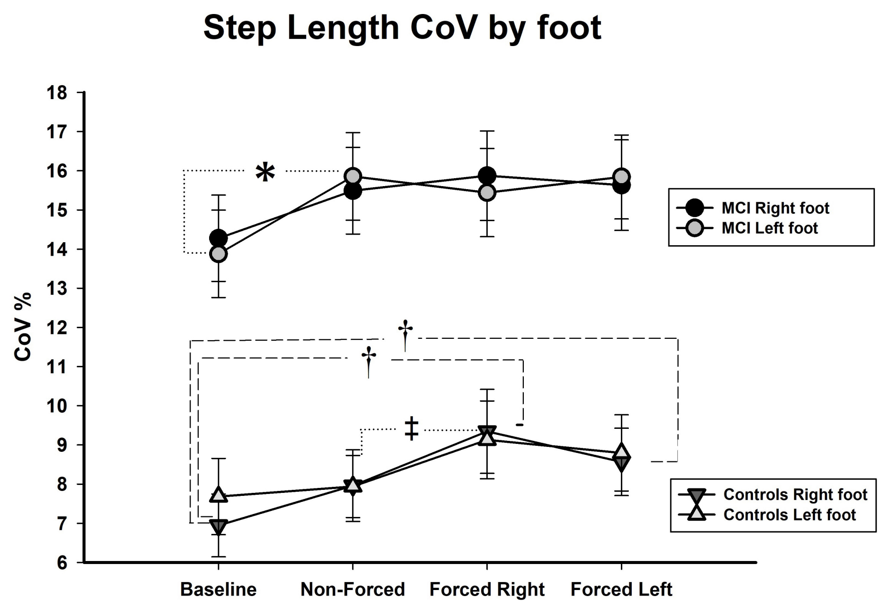

FIGURE 4 | CoV, coefficient of variance, shown in %; aMCI, amnestic mild cognitive impairment; R, right; L, left; (significance level in aMCI shown with *$p < 0.05$; **$p < 0.01$; and ***$p < 0.001$. Significance in healthy controls shown as †$p < 0.05$ for one limb and ‡$p < 0.05$ for both limbs).

length [mean: Pillai's Trace = 0.01, F (1, 93) = 1.13, p = NS; CoV: Pillai's Trace = 0.0, F (1, 93) = 0.16, p = NS]. The same results as those reported in the bilateral analyses regarding main effects for condition and group were replicated for these two variables on both means and CoVs values and therefore, these results are not reported in this section.

However, a main effect of foot was observed on the mean of step width [Pillai's Trace = 0.11, F (1, 93) = 11.30, $p < 0.001$, $\eta^2_p = 0.11$]. This finding indicated that the values of step width were wider for the right foot of all participants disregarding group. Furthermore, the main effect of group already observed in the bilateral analyses was equally present in the lateralized analyses. Nevertheless, this time we could note that the differences between feet were larger for aMCI group than for controls (see **Table 3**). In spite of this finding, no significant Foot × Group interaction existed. Interestingly, no main effect of foot was observed on the CoV of step width [Pillai's Trace = 0.00, F (1, 93) = 0.41, p = NS], which agrees with the lack of main effects for group and condition already observed on this exact variable in the bilateral MANOVA.

Controlling for effects of hearing on lateralized gait parameters: In line with the approach applied on the bilateral analyses, we also conducted a series of factorial MANCOVAs with Best PTA as covariate on the lateralized assessments. Results showed no significant effects of the covariate in the mean of all three gait measures or on the CoVs of gait speed and step width. Nonetheless, we found an exception for the CoV of step length in which Best PTA affected the original results by nullifying a significant interaction and causing the occurrence of two new significant interactions. First, we found that the interaction between Condition × Group became non-significant after controlling for hearing status [Pillai's Trace = 0.08, F (3, 90) = 2.51, p = NS]. Second, the appearance of a significant interaction between Condition × Foot [Pillai's Trace = 0.08, F (3, 90) = 2.75, $p < 0.05$, $\eta^2_p = 0.11$] and between Condition × Foot × Group [Pillai's Trace = 0.08, F (3, 90) = 2.63, $p < 0.05$, $\eta^2_p = 0.08$] were seen after controlling for Best PTA. Analyses of simple main effects revealed that aMCI participants displayed significantly higher CoVs ($p < 0.05$) for left foot in the NF condition as compared to Baseline (see **Figure 4**). No further significant differences for the aMCI group were seen in left or right foot variability across the dual-task conditions.

Regarding the healthy control group, several findings yielded. To begin with, there was observed a significant increment in variability on both the right and the left foot ($p < 0.05$) during the FR as compared to NF condition (see **Figure 4**). Also, step length variability of right foot increased significantly during the FR ($p < 0.001$) and the FL ($p < 0.01$) conditions as compared to Baseline.

DISCUSSION

In the present study, individuals with amnestic MCI and cognitively healthy older controls performed a dual-task paradigm consisting of a dichotic listening task simultaneously to over-ground walking. The main goal was to determine whether spontaneous vs. volitional focus of attention evoked quantitative and qualitative impairments on gait in aMCI individuals as compared to healthy controls. As in any complex dual-task situation, we found that performing DL while walking compromised quantitatively all gait parameters in the aMCI group. The aMCI group showed worse mean values in all conditions, in regard to slower gait speed, shorter step length, and wider step width. However, the aMCI group's CoVs were significantly higher for step length and gait speed during the forced attention-conditions. No increment was found on step width CoV. Thus, these data confirm that our dual-task paradigm posed heavier demands for the individuals with aMCI particularly during volitional control of attention.

However, we also expected qualitative differences in the aMCI group, such as asymmetric gait outcomes related to lateralized focus of attention. This was not the case. Only after adjusting for hearing status, we observed a significant asymmetric increment on step length variability of left foot in the aMCI group during the NF condition. No further significant asymmetries were seen in this group. It could be argued that this is a main finding in our study, but a closer scrutiny to **Figure 4** shows that the result could be incidental. Indeed, the significant result offers a hint to the possible moderating role hearing loss might exert on step length variability of these individuals. Notwithstanding, we rather believe that the main finding of this investigation relies on the *lack* of asymmetries in the aMCI group. In fact, the difference in number of significant asymmetries that arose in healthy controls and not in aMCI participants after controlling for hearing status is worth noting.

After adjusting for Best PTA, significant asymmetries were disclosed in the control group related to increased step length variability of their right foot in all conditions, though the effect was more evident during the forced-attention conditions. Usually, asymmetries are regarded as deleterious or linked to pathology in older populations (Verghese et al., 2008; Yogev-Seligmann et al., 2008). Therefore, our interpretation has been that asymmetries in healthy older adults evoked by directing attention to one specific ear are detrimental. However, in the present study, without accounting for hearing status, these effects get masked and their emergence after controlling for Best PTA -thresholds suggests a link to good auditory compensation. This interpretation was also reported in our study from 2018 (Gorecka et al., 2018). In short, healthy elders have better hearing acuity than aMCIs across all audiometric outcomes, which indicates that controls had better perceptual abilities that enable them to perform the task appropriately and for this reason the asymmetries evoked may represent a risk of falling in healthy seniors.

Now, the question is why aMCIs did not display as many asymmetries as controls and the answer may rely on performance of the DL task. As mentioned in the introduction, dichotic listening tasks have been usually applied in MCI persons for the assessment of hearing ability (Swords et al., 2018), which limits information about the exact nature of attentional/executive disabilities of this population during performance of DL. In the present study, even if the aMCI group reported more responses from the right side (regardless of the task's instructions), the number of correct responses across conditions did not differ significantly between groups. In spite of no group differences, aMCIs clearly showed a difficulty to direct attention to left ear as denoted by the laterality indexes (LIs). This finding is understandable as aMCI individuals present not only memory difficulties but also executive impairments (Johns et al., 2012; Rabi et al., 2020), which are documented by the neuropsychological results of our study. Notwithstanding, the LIs not only point to the aMCI group's difficulty in focusing on the non-dominant ear. On one hand, LIs revealed that the aMCI group had less REA in the NF condition than healthy controls, indicating troubles in bottom-up processing based on perceptual salience of the stimulus material (Kaya and Elhilali, 2014), which can be related to their hearing difficulties. On the other hand, aMCI participants did not show a clear attentional focus for any side, as their LIs were rather similar during the NF and FR conditions. Thus, these findings suggest a lack of lateralized attentional capacity to attend auditory stimuli, which hinders them to properly direct their attention to any specific side.

Still, the aMCI group's gait becomes compromised, though, not asymmetrically.

The reason for having difficulties in the DL task during walking are various and not necessarily only based on executive dysfunctions. It is certain that the main sources of their inability to perform DL are associated to executive impairments and hearing troubles. Still, the aMCI individuals could have neglected to adequately execute the dual-task due to prioritization of walking. It has been shown that just "walking while talking" is a demanding task for some type of elders (Lundin-Olsson et al., 1997). Thus, a too complex cognitive task such as DL while walking, imposing too much cognitive load causes older individuals with cognitive impairment to take a cautious and more secure walking strategy (Cederwall et al., 2014; Montero-Odasso et al., 2014). Hence, it is possible that the aMCI group adopted a "posture first"- strategy (i.e., they might have prioritized the walking) (Yogev-Seligmann et al., 2012), in spite of being required to perform as well as possible, both the walking and attending the DL test. This highlights the importance of selecting appropriately difficulty level for the concomitant task (see Montero-Odasso et al., 2014; Bishnoi and Hernandez, 2020). For instance, the Bergen Dichotic Listening Test that was applied in this study is based on syllables as auditory stimuli. It may have proved difficult for aMCI participants to perceive and differentiate between these sounds, due to their heavier hearing difficulties. It is reported that effortful listening in older people increases cognitive load (Carr et al., 2020). Thus, not being able to fully perceive sounds successfully, might have increased the cognitive load during execution of DL and under such circumstances, auditory and motor processes may compete for limited resources (Bruce et al., 2017). Based on the above, it is plausible that implementation of another DL paradigm relying on the use of meaningful words may promote asymmetric effects as those seen in healthy controls. Therefore, future studies evaluating individuals with MCI should apply DL paradigms involving regular or familiar words for easier recognition (Westerhausen and Samuelsen, 2020) and confirmation of the present findings such as simple numbers (Klichowski and Kroliczak, 2017) or sentences like the "Dichotic sentence identification test" (Jerger et al., 1994).

Another possible reason related to the lack of asymmetries in the aMCI group, concerns the walking setting in our study. In most dual-tasks studies, participants are required to walk for shorter distances and in a linear fashion on a walkway. In our paradigm, subjects walked straight as well as negotiate the turns to follow the circuit within the walking area, which requires adjusting their walking accordingly. Memory and executive functions are necessary to maintain a safe gait, and deficits in these cognitive domains affect the ability to estimate hazards in balance and navigation (Montero-Odasso et al., 2017) such as the turns in the Optogait field. In a recent study, by Pieruccini-Faria et al. (2019) it has been demonstrated that executive functions have a mediating role in abnormal gait control and gait adjustments, meaning by this that persons with executive impairments cannot judge appropriately environmental hazards. Consequently, the walking design of the present study could have contributed to the prioritization of walking in aMCI individuals as turning poses additional challenges to walking (Sunderaraman et al., 2019).

In line with the previous argument, the counterclockwise direction adopted in our study may potentially have an impact on the results. To our knowledge, no study has been conducted to compare asymmetric effects of walking directions on spatio-temporal gait data and this yields for any type of population. However, a study by Caballero et al. (2019), showed no significant differences on walking kinematic variability between clockwise or counterclockwise walking directions. Thus, because right-handers tend to prefer a counterclockwise walking direction (Mohr et al., 2003), and walking turn preference has been reported to work as a stabilizing factor in walking (Lenoir et al., 2006) we believe that the adopted walking direction should not have a substantial effect on our results, at least on the cognitively healthy controls. Notwithstanding, data from our laboratory (Rodríguez-Aranda et al., 2018) and other researchers (Liu et al., 2018) indicate that right-handed MCI individuals undergo abnormal lateralized abilities that might cause alterations on walking preferences. Thus, future studies are encouraged to apply other walking alternatives to evaluate whether the present findings rely on the sole use of DL, independent of walking environment, or whether gait alterations due to DL are tightly related to the experimental situation.

All in all and based on the findings the most parsimonious interpretation is that our data point to a combination of auditory and attentional constraints that impeded good task-execution in aMCI individuals and hence, a lack of asymmetries. For this reason, we wish to deepen into the interplay of hearing, cognition and walking among aMCIs and healthy elders.

Interplay of Hearing Loss, Attentional Abilities and Gait Perturbations in Normal Aging and aMCI

Results of the present study suggest that different levels of hearing loss and attentional decline in two groups of older adults interact differently during execution of dichotic listening while walking. The appearance of asymmetric effects on step length variability seems to be a perturbation related to normal aging, while the lack of asymmetries but exaggerated variability increments on gait needs to be regarded as pathological and proper to aMCI. These outcomes are of interest, and they contribute to better understanding the interplay of cognitive and sensory-motor changes in the aging continuum.

There are scarce empirical data about how concomitant disabilities such as hearing decline and attentional impairments affect functional aspects of older persons, such as gait. Much information exists coupling peripheral hearing loss with central auditory dysfunction, and risk factor for dementia (e.g., Thomson et al., 2017). Also, several cross-sectional and longitudinal investigations have reported a link between hearing loss, cognitive decline and frailty in older populations including community dwelling elders (Kamil et al., 2016), as well as those suffering of MCI and Alzheimer's disease (Rahman et al., 2011; Panza et al., 2015; Wayne and Johnsrude, 2015). It must be highlighted that the link between hearing loss and cognitive decline in aging is not a new one (e.g., Lin et al., 2013). In contrast, the suggestion that these ailments are tightly related to frailty, and specifically to its operationalization based on gait impairments is a more recent observation (Ayers and Verghese, 2019; Panza et al., 2019; Cheng et al., 2021). Because, we are still far from understanding the real nature of these associations, we believe that the present study is a step forward to unveil how concrete cognitive constraints, such as attentional control dependent on hearing acuity affects gait in aMCI. In addition, our results have clinical implications since we have focused on aMCI, which is the MCI subtype most susceptible to progress into Alzheimer's dementia. Since MCI subtypes are proposed to differ in neuropathology (see Doi et al., 2017), gait outcomes in dual-tasking are expected to vary accordingly. Though, so far, few dual-task studies have been conducted as an attempt to distinguish between non-amnestic and amnestic MCI (for review, see Doi et al., 2014; Montero-Odasso et al., 2014; Tseng et al., 2014; Bishnoi and Hernandez, 2020). The present findings suggest that in order to properly establish differential profiles based on MCI subtypes, cognitive and sensory declines need to be integrated.

Limitations and Strengths

There are some limitations of this investigation that should be acknowledged. The lack of DL as single-task can be regarded as a weakness of our study. Many dual-tasks paradigms assess the motor and cognitive tests as both single and during dual-tasking. However, since we wished to evaluate the effects of the experimental situation without previous exposure to DL, we intentionally did not assess the cognitive test as single task. A similar approach has been adopted in several studies that equally have only assessed single-task performances in cognition (Al-Yahya et al., 2011). In the current study, the rationale of avoiding single-execution of DL was important to appraise the effects of this over-ground dual-task paradigm as a novel situation and as a more ecological approach where participants were naïve to the cognitive task. However, the interest of applying DL as single test among aMCI participants is evident and future research should include DL as a single-task (both the Bergen DL test and other variants) to deepen into the executive abilities of aMCI as well as to assess the effects of previous exposure of DL in the dual-task paradigm.

Another limitation is that we have not explored whether the walking direction (i.e., counterclockwise) and/or settings (i.e., walking in circles) may impact the results. Future investigations are encouraged to address these issues by conducting the present paradigm in straight walking environments and by comparing outcomes from different walking directions. Also, it is important to acknowledge that while our group of aMCI is well defined and the amnestic subtype is the most prone to convert into Alzheimer's dementia (Ward et al., 2013), not everyone with such a diagnosis develop dementia (Langa and Levine, 2014). In fact, the certainty of the diagnosis can only be achieved after a follow-up assessment (Sun et al., 2019). This means that only through a longitudinal evaluation we would be able to assert whether the present paradigm can be used in the early detection of AD.

Despite the limitations of the present study, we wish to highlight some important strengths. In addition to the application of an ecologically valid paradigm, we regard the selection of the patient group as important. The aMCI participants recruited in our study were referred from the University Hospital of North Norway with a clinical diagnosis of MCI. Thereafter, these participants underwent a thorough neuropsychological assessment, which enabled correct classification into MCI subtypes. Compared to many aging studies dealing with a wide category of MCI, who are recruited from the community and are often categorized in MCI upon single measures of cognitive status (e.g., MMSE score), our criteria for aMCI inclusion provides clinical trustworthiness to our findings. We used several measures within each cognitive domain to determine not only subtype of MCI but also to ensure normal cognitive status of controls. Many studies apply too few measures representing different cognitive domains, which prove not to be sufficient (Clark et al., 2013). By having the certitude that the MCI group in this current study is properly classified as aMCI, we also assert that this sample indeed displays mixed difficulties of memory and executive dysfunctions. Rabi et al. (2020) suggested that individuals properly categorized as aMCI from clinical samples, not only show higher conversion to Alzheimer's Disease but also perform significantly worse on measures of executive functions than community-based samples. This in turn allows us to claim that the difficulties to perform DL task by the aMCI group are strongly related to executive impairments and higher levels of hearing loss.

Clinical Implications and Future Directions

Challenging everyday actions such as dual-tasking depend heavily on cognitive resources but also on adequate hearing and free walking. The present approach reveals the importance to assess multiple bodily and cognitive changes affecting older adults that are in need of preserving their autonomy as long as possible. Applying DL with gait assessment may provide a cost-efficient and sensitive measure to detect gait difficulties, cognitive dysfunction, and auditory difficulties in older adults with a probable risk of developing dementia. Since older adults with hearing loss are at greater risk of falls, audiological assessment in addition to thorough cognitive evaluation and gait analysis may be important in providing a holistic approach to aid activities of daily living in older adults with MCI. The association between cognition, hearing loss and gait disturbances provides an interdisciplinary approach in assessment and shows that a targeted audiological rehabilitation could be used to complement physical and cognitive rehabilitation in older adults.

Furthermore, we consider that the clinical application of the present paradigm has a great potential on the differential diagnosis of various MCI subtypes. For instance, results of the present study can be compared to the rest of the traditional MCI subgroups. Though, because our paradigm tightly involves a motor element (walking), hearing ability and their interplay to lateralized attentional/executive capacities, other MCI subtypes more prone to present impairments in these areas represent a fruitful venue of exploration. The recent criteria proposed for prodromal Lewy-Body Dementia (LBD) and Parkinson's Disease Dementia (PDD) (McKeith et al., 2020; Pieruccini-Faria et al., 2021) offers good examples. It has been reported that auditory hallucinations are an important characteristic for LBD and PDD (Eversfield and Orton, 2019) and in turn, hallucinations have been related to greater hearing loss, mainly in PDD (Lai et al., 2014). In addition, it is suggested that MCI for LBD and PDD characterizes by important executive impairment which has been successfully evaluated with the Stroop test (Belghali et al., 2017). Thus, application of the present paradigm with dichotic listening offers a good alternative that relies on an ecologically valid environment. In sum, it is appealing to consider in future research the use of dichotic listening while walking in the differential diagnosis of prodromal LBD and PDD.

CONCLUSION

Results of the present study demonstrate that the interplay between cognitive status, hearing loss and gait perturbations differs between cognitively healthy older adults and individuals with aMCI. Asymmetric effects on step length variability were evident in controls who were able to perform DL task appropriately. In contrast, symmetric gait variability increased overly in aMCI participants due to lack of cognitive and auditory abilities that enabled them to execute the DL test. Thus, the association between hearing, cognition and gait in older populations is undisputable, but based on our findings the interactive mechanisms are not so easy to seize. Outcomes may depend upon degree of impairment and task difficulty. In addition, other factors such as task prioritization, novelty in the walking environment and practice may have a further impact in the results. Future studies should further investigate the importance of these aspects in different MCI subtypes.

Application of the present dual-task paradigm with aMCI individuals stresses the importance of considering sensory loss when assessing the mechanisms behind dual-task decrements in older adults with cognitive impairment. From a clinical perspective, it is crucial to understand the moderating role of hearing loss in cognition and functional abilities, especially related to how these deteriorations enhance the risk of dementia development. Therefore, we consider that the present paradigm is a suitable alternative to better understanding of the sensory-motor-cognition triad of hearing loss, gait perturbations and executive impairments in MCI.

As exposed by authorities in the field, there is a need to improve the methods used to understand the cognition-gait association link in specific populations of older adults (Montero-Odasso et al., 2019). Currently, the cognitive tasks suggested for dual-task paradigms rely on complex and intertwined cognitive abilities with no predominant involvement of a specific sensorial modality. Probably therefore they affect gait at a rather general level, perturbing many spatiotemporal parameters. Thus, we believe that the present findings are a step forward to improve an understanding of how specific attentional constraints in the auditory modality affects concrete gait characteristics. It is still early to declare whether our paradigm is a suitable assessment method for the detection of aMCI as we have to assert adequate difficulty level of DL and the possible differential strength of this method for different MCI subtypes at the long term. Nevertheless, application of dichotic listening on dual-task paradigms provides a promising multicomponent assessment tool for the early detection of cognitive impairment and future studies should account for other decrements in sensory functions such as visual acuity or balance.

DATA AVAILABILITY STATEMENT

The datasets presented in this article are not readily available because this study is part of an ongoing umbrella project and data will be available upon request to the PI at the end of data collection. Requests to access the datasets should be directed to CR-A, claudia.rodriguez-aranda@uit.no.

ETHICS STATEMENT

The studies involving human participants were reviewed and approved by Regional Committee for Medical and Health Research Ethics—REK (2009/1427). The patients/participants provided their written informed consent to participate in this study.

AUTHOR CONTRIBUTIONS

CR-A and MG contributed with the conception and design of the study, performed the statistical analyses, and wrote the draft. MG and OV recruited participants and collected the data. KW helped with the overall logistics and revised intellectual content. All authors contributed to manuscript revision, read, and approved the submitted version.

FUNDING

Financial support was provided from the Norwegian Health Association (2018/A68412 and 2014/888) and from the Faculty of Health Sciences, UIT—the Arctic University of Norway (2016/5455).

ACKNOWLEDGMENTS

We would like to thank the Department of Geriatrics and the Department of Neurology at the University Hospital of North

Norway for help with the recruitment of participants. We would also like to thank Maja Bergman, Barbro Abrahamsen and Jesper Solheim Johansen for help with data acquisition. We would also further like to thank Thomas Nermo and Jørgen Sundby for performing the photo session of the experimental situation.

SUPPLEMENTARY MATERIAL

The Supplementary Material for this article can be found online at: https://www.frontiersin.org/articles/10.3389/fnagi.2021.718900/full#supplementary-material

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Conflict of Interest: The authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

TABLE 1 SUPPLEMENTARY MATERIAL

Results for bilateral gait parameters by group

	CONDITION									
	Baseline		Non-Forced		Forced-Right		Forced-Left			
	Controls	aMCI	Controls	aMCI	Controls	aMCI	Controls	aMCI	RMANOVA, *p, (η^2_p)*	ANCOVA, *p, (η^2_p)*
	M (SD)	*M (SD)*	*M (SD)*	*M (SD)*	*M (SD)*	*M (SD)*	*M(SD)*	*M(SD)*	Cond./Interac./Group	Interac./Group/PTA
Mean										
Step length	64.0 (8.9)	55.5 (8.9)	60.6 (9.6)	51.8 (9.3)	59.1 (9.5)	50.9 (8.8)	59.1 (9.6)	50.4 (9.1)	**0.001 (0.5)**/ NS/**0.001 (0.9)**	NS/**0.001 (0.3)/0.003 (0.1)**
Gait speed	1.1 (0.2)	0.8 (2.2)	1.0 (0.2)	0.8 (0.3)	0.9 (0.3)	0.7 (0.2)	0.9 (0.3)	0.7 (0.3)	**0.001 (0.5)**/NS/**0.001 (0.2)**	NS/**0.001 (0.3)/0.003 (0.1)**
Step width	9.3 (3.4)	13.2 (3.1)	9.5 (2.8)	13.1 (3.2)	10.0 (4.1)	13.1 (3.6)	10.3 (3.7)	13.3 (3.7)	NS / NS/ **0.001 (0.2)**	NS/**0.001 (0.1) /0.001 (0.1)**
CoV (%)										
Step length	7.5 (6.1)	14.2 (6.8)	8.3 (5.9)	15.7 (7.1)	9.6 (7.0)	15.7 (7.2)	8.9 (6.5)	15.8 (7.1)	**0.001(0.0)**/NS /**0.001(0.2)**	NS/**0.001(0.1) /0.001 (0.2)**
Gait speed	8.5 (9.3)	20.6 (11.6)	9.4 (8.7)	21.6 (10.7)	12.8 (15.5)	25.8 (29.7)	11.9 (14.5)	26.6 (35.7)	NS / NS / **0.001(0.2)**	NS/**0.001(0.1)/0.027(0.1)**
Step width	87.0 (46.9)	93.6 (37.6)	81.9 (30.9)	85.2 (30.1)	87.3 (29.7)	87.9 (29.5)	87.1 (34.7)	85.2 (27.9)	NS / NS / NS	NS/ NS / NS

Note. RMANOVA and ANCOVA with Bonferroni correction for multiple comparisons. Units for Step length, Step width and Stride length = cm.; units for Gait speed = m/sec. Abbreviations: *M* = mean; *SD* = standard deviation; RMANOVA = repeated measures analysis of variance; ANCOVA = Analysis of covariance; CoV = Coefficient of Variation; Interac. = Interactions; PTA = Best Pure Tone Audiometry values; NS = Non Significant; CoV = Calculated with the formula: [mean/ SD] x 100%

Errata

Paper II:

Dichotic listening while walking: A dual-task paradigm examining gait asymmetries in healthy older and younger adults

1. Captions to Table 4 and 5
   a. Original formula: (mean/SD) * 100
      Correct to: (SD/mean) * 100
2. Captions Supplementary table I and table II
   b. Original formula: (mean/SD) * 100
      Correct to: (SD/mean) * 100
3. Sentence on page 804:
   Roughly, the literature in laterality proposes that right-brain hemisphere specializes in language while the left-brain hemisphere specializes in non-verbal information, somatosensory and spatial functions.
   Correct to
   Roughly, the literature in laterality proposes that ***left-brain*** *hemisphere specializes in language while the* ***right-brain*** *hemisphere specializes in non-verbal information, somatosensory and spatial functions.*
4. Captions Supplementary Table I & II
   Original text: PTA = Best Pure Tone Audiometry values
   Correct to: PTA = Worst Pure Tone Audiometry values